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BULLETIN OF THE GEOLOGICAL SOCIETY OF NORFOLK

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EDITORIAL

It is not uncommon that rare palaeontological finds are made by children of school age. In 2004 ten year old Thomas Knight was lucky enough to spot a very rare Cretaceous shark tooth in the Red Chalk at Hunstanton. He was also lucky enough to have a father who realized the significance of the find. Following initial contact with the GSN the tooth was passed on for expert scrutiny and the outcome is described by Peter Smart here in Bulletin No. 55. This issue should also please those with interests in the Quaternary geology of Norfolk. There is a detailed description of the glacial stratigraphy of the Briton's Lane borehole and quarry near Sheringham, and the topical debate about the first appearance and significance of Scandinavian erratics in East Anglian tills continues in a spirited discussion and reply.

At the time of going to press (October 2005) there are three more papers almost ready for publication and more new contributions are promised. I anticipate Bulletin 56 appearing early in 2006 and especially thank regular contributors for their support. I look forward to continued submission of papers on all aspects of East Anglian geology, from both regular and new contributors.

INSTRUCTIONS TO AUTHORS

Contributors should submit manuscripts as word-processor hard copy. We accept typewritten copy and consider legible handwritten material for short articles only. When papers are accepted for publication we will request an electronic version. We can handle most word-processing formats although MS Word is preferred.

It is important that the style of the paper, in terms of overall format, capitalisation, punctuation etc. conforms as strictly as possible to that used in Vol. 53 of the Bulletin. Titles and first order headings should be capitalised, centred and in bold print. Second order headings should be centred, bold and lower case. Text should be 1½ line spaced. All measurements should be given in metric units.

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STEERS, J.A. 1960. Physiography and evolution: the physiography and evolution of Scolt Head Island. In: Steers, J.D. (ed.) *Scolt Head Island* (2nd ed.), 12-66, Heffer, Cambridge.

BLACK, R.M. 1988. *The Elements of Palaeontology*. 2nd Ed., Cambridge University Press, Cambridge. 404pp.

Illustrations should be drawn with thin dense black ink lines. Thick lines, close stipple or patches of solid black or grey should be avoided as these can spread in printing. Original illustrations should, before reproduction, be not more than **175mm by 255mm**. Full use should be made of the first (horizontal) dimension which corresponds to the width of print on the page, but the second (vertical) dimension is an upper limit only. Half tone photographic plates are acceptable when their use is warranted by the subject matter, provided the originals exhibit good contrast.

The editors welcome original research papers, notes, comments, discussion, and review articles relevant to the geology of **East Anglia** as a whole, and do not restrict consideration to articles covering Norfolk alone. All papers are independently refereed by at least one reviewer.

A VERY RARE TOOTH OF THE HEXANCHID SHARK *NOTORYNCHUS APTIENSIS* FROM THE ALBIAN RED CHALK OF HUNSTANTON CLIFFS

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ABSTRACT

Remains of vertebrates, including teeth and bones of fish, are rare in the Lower Cretaceous Hunstanton Red Chalk Formation at Hunstanton in north West Norfolk. With only a few incomplete or fragmentary teeth known from this deposit, the discovery, by Thomas Knight in 2004, of a well preserved lower jaw anterolateral tooth of the hexanchid shark Notorynchus aptiensis (Pictet 1865) was an extremely rare event. This paper describes this tooth and illustrates other known Red Chalk material from the Hunstanton cliffs.

INTRODUCTION

In 2004 a well preserved lower jaw anterolateral tooth of the hexanchid shark *Notorynchus aptiensis* (Pictet 1865) was discovered by Thomas Knight, ten year old son of scientist Dr. Kevin Knight, while on holiday at Hunstanton. The tooth came from a fallen block of Lower Cretaceous Hunstanton Red Chalk Formation. With only a few incomplete or fragmentary teeth known from this bed, it was an extremely rare find. Hexanchid sharks (Order Hexanchiformes, Family Hexanchidae) are first recorded from Jurassic sediments, represented by the genera *Eonotidanus* and *Hexanchus*, the genus *Notorynchus* appearing in the early Cretaceous as the single species *Notorynchus aptiensis* (Pictet 1865) which is known only from rare isolated teeth. The family is characterised not only by strong monognathic and dignathic heterodonty in the dentition but also by the multicuspid anterolateral teeth (for unfamiliar terms see glossary). For this reason Lydekker (1896) referred to them as "comb-toothed" sharks, a more definitive

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term than the current "six and seven gilled sharks", particularly for fossil species where anatomical structure is not known

Prior to 1987 only three teeth of *N. aptiensis* had been described from UK early Cretaceous sediments, although others have been described from France and Germany (Ward & Thies 1987). Subsequently, sixteen anterolateral teeth from inland deposits of Albian Gault clays were described and later donated to the Natural History Museum (Smart 1995; 2001). Some of these are imperfect in some morphological details, particularly regarding brittle cusps which have lost apices, or roots that are eroded away.

It is of particular interest that Thomas Knight's specimen (described here and shown in Fig. 1a) is in a very good state of preservation compared to the few other teeth known from the Hunstanton Red Chalk (collection of Mr. M. Hurn and shown in Fig. 2). The crown is complete apart from slight erosion of the extremities, the root being eroded below the principal cusp. The tooth's rarity is exemplified by the absence of Hunstanton teeth of *N. aptiensis* in major depositories including the Natural History Museum, the Sedgwick Museum, Cambridge, and the Norwich Castle Museum. Even the extensive private collection of Red Chalk material from Hunstanton cliffs donated to the Natural History Museum by Mr. Hamon Le Strange, who collected from the early 1920s, contains no hexanchid teeth: indeed Le Strange remarked on the rarity of fish remains in the Hunstanton Red Chalk.

STRATIGRAPHY

The most comprehensive modern account of the stratigraphy of the Carstone Formation and overlying Hunstanton Red Chalk Formation at Hunstanton is by Owen (1995). Previously, the most accurate stratigraphical account was given by Wiltshire (1869) and is still the framework used today (Owen 1995, p. 171). Wiltshire recognised three distinct lithological units of beds which he labelled A, B and C in downward succession: Owen (1995) subdivided these based predominantly on Zone and Subzone index fauna.

Fossils found in the Hunstanton Red Chalk Formation have long been recognised as a Gault fauna (see e.g. Sedgwick 1826). However, ammonite and bivalve faunas show that the Red Chalk sediments at Hunstanton form a very incomplete sequence compared to the Gault Formation elsewhere. It is therefore possible that the extreme rarity of vertebrate remains, which can be reasonably frequent as teeth and bones of fish at some

Fig. 1a. *Notorynchus aptiensis* (Pictet 1865). Right lower jaw anterolateral tooth (LA-L 6) in matrix, discovered by Thomas Knight in the Albian Hunstanton Red Chalk Formation. ? *Mortoniceras inflatum* Zone, *Hysteroceras orbignyi* Subzone, Hunstanton Cliffs, Norfolk, near TF 6777 4230. T. Knight collection, 2004.

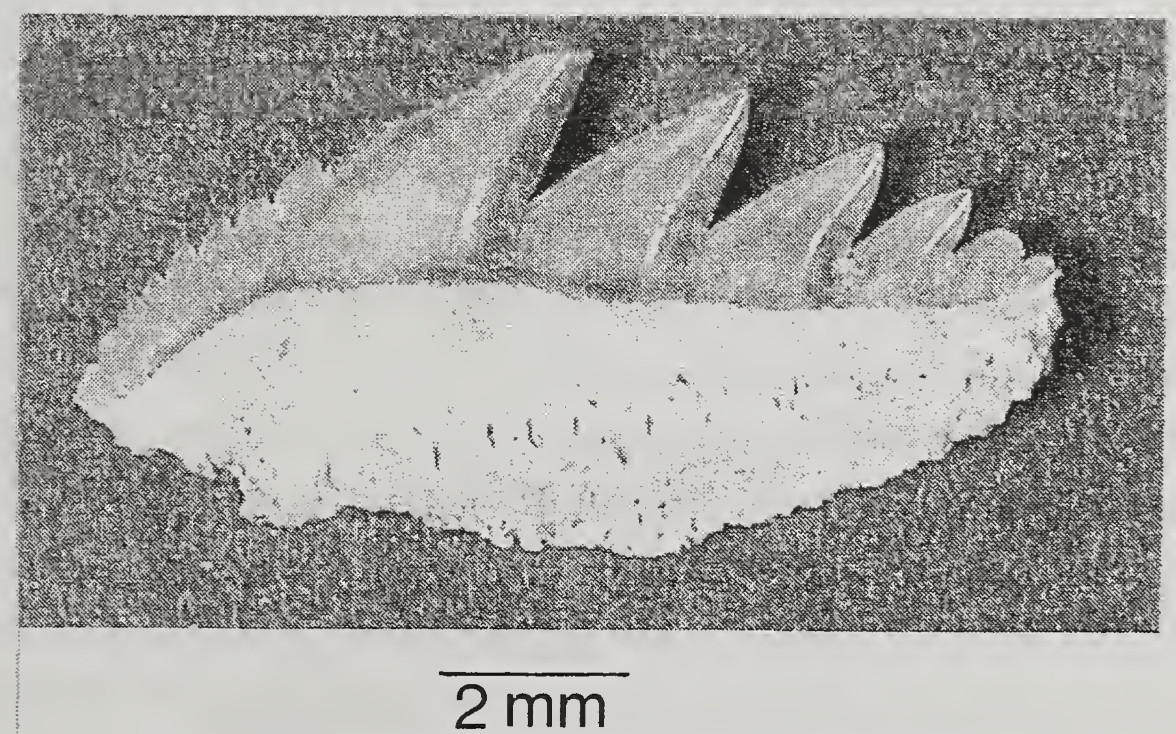

Fig. 1b. Right lower jaw anterolateral tooth (LA-L6) from Albian Gault clays. *Euhoplites loricatus* Zone, *Dimorphoplites niobe* Subzone, Mundays Hill quarry, Leighton Buzzard, Bedfordshire, near SP 936 279. P.J. Smart collection, 1995.

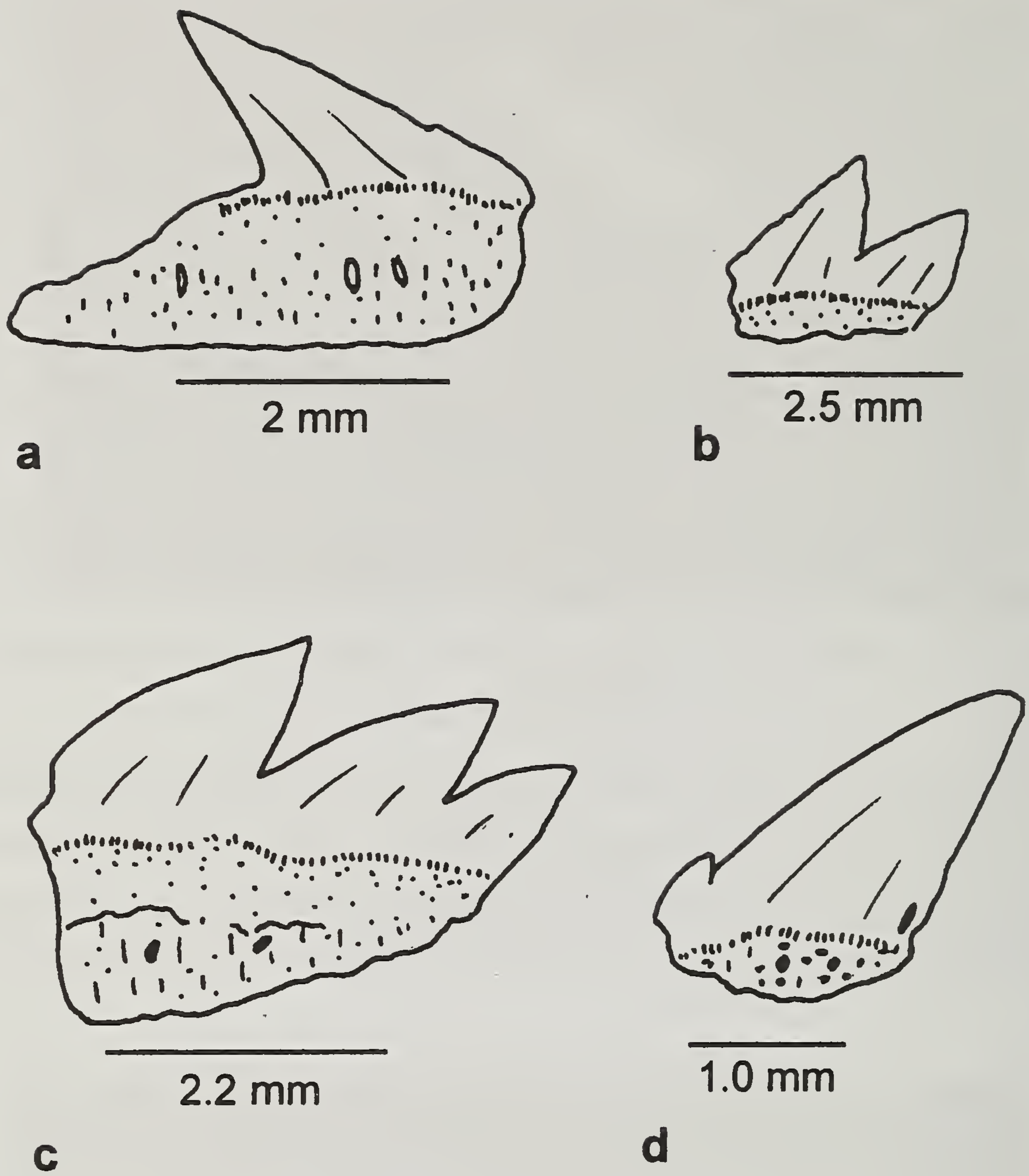

Fig. 2. *Notorynchus aptiensis* (Pictet 1865). Other known teeth from the Hunstanton Red Chalk Formation of Hunstanton Cliffs, Norfolk. (a) ?Upper anterolateral tooth. Distal cusps missing and principal cusp serrae eroded. Lack of mesial depression indicates upper jaw. M. Hurn collection, H 107. (b) Fragmentary sub-juvenile anterolateral with partial principal cusp and biconvex first distal cusp. M. Hurn collection, H 171. (c) Juvenile lower anterolateral with 3 distal cusps and eroded root.M. Hurn collection, H 216. (D) Subjuvenile principal cusp with upper remnant of crest of mesial margin serrae. M. Hurn collection, H 173.

Gault horizons, is a result either of such horizons being partially or totally absent at Hunstanton or due to different oceanic conditions in the region during Albian times.

SYSTEMATIC PALAEONTOLOGY

The dental terminology used in this paper is based largely on Cappetta (1987).

Subclass *Elasmobranchii*, Bonaparte, 1838
Superorder *Squalomorphi* Compagno, 1973
Order *Hexanchiformes* Buen, 1926
Suborder *Hexanchoidei* Garman, 1913
Family *Hexanchidae* Gray, 1851
Genus *Notorynchus* Ayres, 1855

Notorynchus aptiensis (Pictet 1865)

MATERIALS

One lower jaw anterolateral tooth from Hunstanton cliff Red Chalk partly embedded in a very hard pink coloured matrix (Fig. 1a); one similar lower anterolateral tooth from Albian Gault (Fig. 1b) and four fragmentary anterolateral teeth (Figs. 2a - d) from the Red Chalk at Hunstanton.

DENTITION

Although *Notorynchus aptiensis* is to date known only from rare isolated teeth, all have been recorded and establish that a complete dentition does not differ fundamentally from that of the extant *N. cepedianus* shown and annotated in Fig. 3. The strong disjunct monognathic and dignathic heterodonty characteristic of the Hexanchidae is clearly recognisable in assemblages of *N. aptiensis* teeth, and only the very small posterior teeth are as yet unknown.

Nevertheless, morphological changes have taken place during the 135 million years from the early Cretaceous (to the present), when the genus *Notorynchus* first appeared (as *N. aptiensis*) in the Hauterivian. For example, the lower jaw median teeth in *N. aptiensis* have been found to possess a high central cusp, an unsuspected feature prior to 1997 when a single adult tooth was discovered in Western Australia (Siverson 1997).

A second adult tooth with this high central cusp was found by the writer in the Albian Gault Clay of Leighton Buzzard, Bedfordshire (Smart 2002), thus establishing this morphological feature in *N. aptiensis* median teeth. It is probable that this high central cusp is gained during ontogeny, being absent in two sub-juvenile median teeth from north-east England (Underwood & Mitchell 1999). However, in the Eocene species *N. serratissimus* and *N. kempi*, which appeared respectively some 45 million and 57 million years later than the Albian teeth of *N. aptiensis* described in this paper, the central cusp is much reduced in height and, in the extant *N. cepedianus*, it is absent.

The anterolateral teeth are also less mesio-distally expanded in *N. aptiensis* than those of *N. cepedianus*, being up to a third narrower and with fewer distal cusps, on lower jaw teeth normally 3 or 4 a rare 5th being an occasional rudimentary cusplet at the crown distal extremity. It is also unusual to find an adult tooth wider than 10.5mm, any such being possibly from larger growing females, if *N. aptiensis* was sexually dimorphic, as is the extant *N. cepedianus*. Two anterolateral teeth of *N. aptiensis* are illustrated in Fig. 4 to clarify the terminology used in the text. Drawn from material in the writer's collection, they are typical upper and lower teeth from files 4-5, as represented in Fig. 3.

DESCRIPTIONS

Fig. 1(a). A lower right jaw anterolateral tooth LA-L6 from an adult shark, lingual view. Principal cusp sloping distally, mesial cutting edge slightly convex with crest of forward pointing serrations along lower margin, serrae increasing in size apically. Distal margin convex, at an angle of 39° to mesial margin of first distal cusp. Distal cusps 4 in number, decreasing in size distally to a rudimentary cusplet, mesial and distal margins convex.

Root low, anaulacorhize, eroded mesially below principal cusp, possibly rectangular when complete and baso-distally convex. Lingual face with prominent longitudinal protuberance with deep vascular furrow and a large eliptical foramin lying on the protuberance. Labial face obscured by matrix, but normally concave.

Root surface affected slightly by the chemical weathering to be expected from salt penetration, the pores and small foramina now indistinct.

Tooth width 11.6mm. Height 6.1mm.

Albian Hunstanton Red Chalk Formation, Hunstanton cliffs, near TF 6777 4230.

T. Knight collection, 2004.

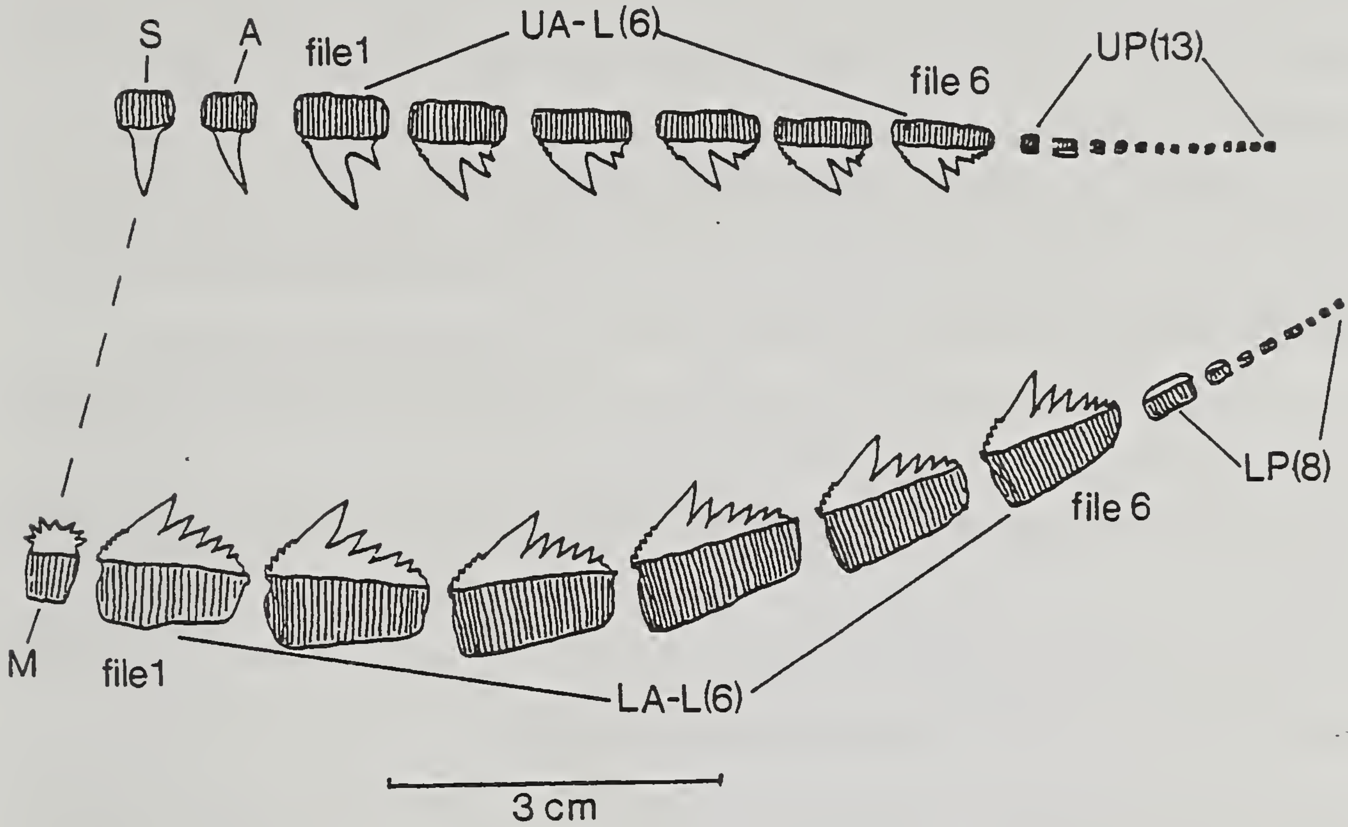

Fig. 3. Dentition of the extant hexanchid shark *Notorynchus cepedianus* (Péron 1807) illustrating the disjunct monognathic and dignathic heterodonty that characterises the Hexanchidae. Drawn from an adult male shark jaw, the shark being 1.8 metres in length. S: Symphyseal tooth; A: Anterior tooth; UA-L: Upper anterolateral teeth; UP: Upper posterior teeth. M: Median tooth; LA-L: Lower anterolateral teeth; LP: Lower posterior teeth.

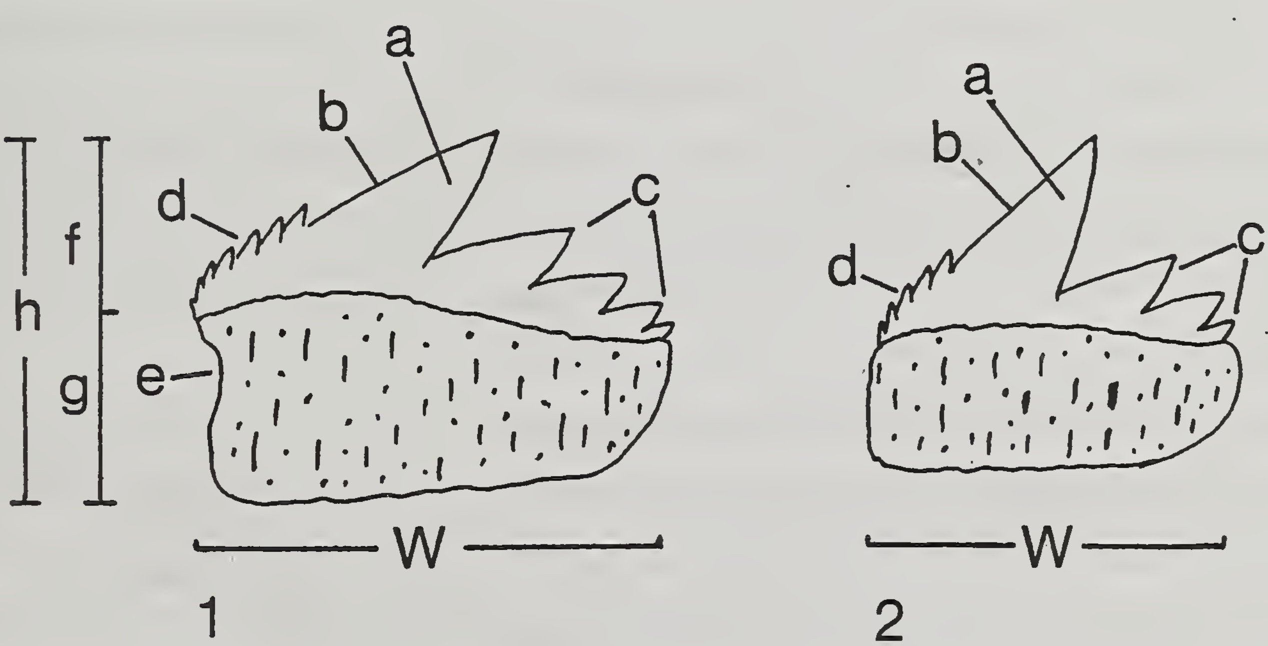

Fig. 4. Morphology of typical *Notorynchus aptiensis* anterolateral teeth, 4th or 5th files (diagrammatic). 1: Lower jaw tooth (LA-L), 2: Upper jaw tooth (UA-L). a: Principal cusp; b: Mesial cutting edge; c: Distal cusps; d: Mesial margin serrations; e: Mesial depression (LA-L); f: Crown; g: Anaulacorhize root; h: Tooth height; w: Tooth width.

Fig. 1(b). A similar lower right jaw anterolateral tooth (LA-L6), lingual view, to illustrate the root face fenestrated with numerous pores and foramina when not subjected to erosion.

Tooth width 11.8mm. Height 6.2mm. Middle Albian Gault clay, *Euhoplites loricatus* Zone, *Dimorphoplites niobe* Subzone, Mundays Hill pit, Leighton Buzzard, Bedfordshire, near SP 936279.

P.J. Smart collection, 1995, 15517M.

Fig. 2. Other known *N. aptiensis* teeth from Hunstanton cliff (Hunstanton Red Chalk Formation).

(a) ?UA-L, distal cusps missing. Principal cusp with eroded crest of serrae. Root mainly complete with two vascular furrows and smaller foramina on lingual protuberance.

M. Hurn collection, H 107.

(b) Sub-juvenile crown fragment with partial principal cusp and first distal cusp.

M. Hurn collection, H 171.

(c) Juvenile LA-L fragment with 3 distal cusps and remains of root eroded.

M. Hurn collection, H 216.

(d) Sub-juvenile principal cusp with upper mesial margin serration.

M. Hurn collection, H 173.

DISCUSSION

The location of the tooth found by Thomas Knight was some 300-400 metres southwest of the path through the sand dunes which leads to Old Hunstanton car park from the beach (K. Knight pers. comm. 2004). This places the large blocks of fallen rock from which the tooth was collected in the vicinity of the measured section of Owen (1995, his figure 4). K. Knight's description of the thick, very hard pink rock from which the tooth was collected suggests the "tough pinky-red limestone" of Owen's Bed B(iii) which he recorded as 24cm in thickness. If this is so, the tooth is of Upper Gault *Hysteroceras orbignyi* Subzone age, a Subzone that has yielded occasional teeth of *N. aptiensis* from inland Gault facies in the Leighton Buzzard area.

To conclude, the two teeth shown in Fig. 1 have been attributed to file 6, but at present this is questionable. Of the four extant species of hexanchid shark *Hexanchus vitulus* and *Heptranchias perlo* possess 5 files of very mesio-distally expanded teeth,

Hexanchus griseus and *Notorynchus cepedianus* having 6 files of narrower teeth. Measuring extant shark material in the writer's reference collection, the widest lower anterolaterals of an adult *H. vitulus* (files 2-4) are 22mm wide, those of an adult *N. cepedianus* (files 2-3) being 17mm in width, the rows of teeth in the jaws being 99mm and 88mm in length respectively.

In contrast, the majority of *N. aptiensis* anterolateral teeth in the writer's reference collection, including those previously deposited in the Natural History Museum, are between 9.0mm and 10.5mm in width and suggest an additional (7th) file (Smart 1995). Until a complete dentition is discovered, therefore, the number of anterolateral files in *N. aptiensis* must remain enigmatic.

ACKNOWLEDGEMENTS

I thank Dr. Kevin Knight and his son Thomas for information relating to the Hunstanton tooth and for their interest and the loan of the specimen for examination; also for the excellent photographs. I also thank Mr. Paul Whittlesea for initially putting me in touch with Dr. Knight and for valuable information on Norfolk material, and Mr. Mike Hurn for comments on the Red Chalk and for the photographs in Fig. 2.

My thanks also to Mr. Chris Andrew of Bedford Museum for photographing the specimen in Fig. 1b, and Dr. Peter Forey and Miss Alison Longbottom of the Dept. of Palaeontology, the Natural History Museum, for access to the National Collection. My appreciation also to Dr. Hugh Owen, the Natural History Museum, for information on material donated to the Museum by Mr. Hamon Le Strange, and to Dr. David Norman, Mr. Mike Dorling (now retired) and Mr. Don Pemberton of the Sedgwick Museum, Cambridge, for examining material on my behalf.

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GLOSSARY

Heterodonty (of teeth): having different forms adapted to different functions.

Disjunct: the separation in the nucleus of homologous chromosomes at the anaphase stage of mitosis and meiosis

Monognathic heterodonty: the teeth in one jaw having different morphology.

Dignatic heterodonty: the teeth of upper and lower jaws having different morphology.

Ontogeny: the development of an individual (e.g. tooth) from fertilised egg to adult.

Anaulacorhize: a wide flattened root, the labial face with many small pores and some foramina. The lingual face with longitudinal protuberance and pores, vascular furrow and elliptical foramina.

Dimorphic: exisiting in two forms. Sexual dimorphism in extant *Notorynchus cepedianus* – males up to c. 1.9 m in length and larger females up to c. 2.5 m in length.

Mesial: towards the anterior (front)

Distal: towards the posterior (rear)

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GEOLOGICAL SOCIETY OF NORFOLK WEBSITE

The Geological Society of Norfolk has a website which can be reached at:

http://www.norfolkgeology.co.uk

Details of GSN activities can be found here including:

- Information on the aims and constitution
- Forthcoming meetings, lectures and fieldtrips
- Details of GSN projects
- Details of GSN publications, including instructions for authors
- Information on significant recent finds
- Hot links to other geological websites

THE STRATIGRAPHY OF THE BRITON'S LANE BOREHOLE AND QUARRY, BEESTON REGIS, NORTH-EAST NORFOLK

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ABSTRACT

The Cromer Ridge complex in north-east Norfolk has traditionally been recognised as a push moraine formed during the final retreat of a Scandinavian ice sheet during the Anglian stage. This interpretation is based upon the presence of glaciotectonised North Sea Drift Formation sediments contained within the Cromer Ridge that reportedly include clast lithologies eroded from Scandinavia. Examination of quarry faces and samples from a purpose-drilled borehole at Briton's Lane Quarry on the northern flank of the Cromer Ridge reveal that the ridge has complex, polyphase history. Early-Middle Pleistocene Wroxham Crag Formation gravels are overlain by a thick sequence of intercalated muds and muddy diamictons that were deposited in a large glaciolacustrine basin. These deposits were overridden by two ice advances which deposited the Weybourne Town Till and Bacton Green Till Members of the Sheringham Cliffs Formation. Ice-flow paths reconstructed using derived-clast lithologies, heavy minerals, and allochthonous palynomorphs demonstrate that these ice-advances are British-sourced and further challenge the view that Scandinavian ice deposited the North Sea Drift Formation. The Briton's Lane Sand and Gravel was finally deposited as a large ice-marginal outwash fan following the proglacial deformation of underlying deposits and the construction of the Cromer Ridge.

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INTRODUCTION

The most prominent glacial landform in north-east Norfolk is the 'Cromer Ridge'. The ridge forms a crenulated shaped landform that rises to over 100 m OD and strikes east-west for 14 km between Trimingham and Sheringham with some outlying hills present between Cromer and Weybourne (Straw, 1965; Cox & Nickless, 1972; Hart, 1990; Hart & Boulton, 1991a; Pawley *et al.*, 2004). From Sheringham, the ridge curves to the south-west and extends a further 7 km to Edgefield where the ridge is broken by the 'Briston Gap' before curving west and terminating near Thursford (Fig. 1).

The ridge has traditionally been considered a push-moraine complex, composed of North Sea Drift Formation (NSDF) diamictons and outwash sediments (Table 1) deposited by multiple advances of a Scandinavian ice-sheet during the Anglian-stage (Mitchell *et al.,* 1973; Perrin *et al.,* 1979; Hart, 1990; Hart & Boulton, 1991a; Ehlers & Gibbard, 1991; Lunkka, 1994). However, recent investigations have questioned the provenance of these glacial advances with new lithological evidence demonstrating a Scottish rather than Scandinavian ice-source for the diamictons of the NSDF (Lee *et al.*, 2002, 2004a; Pawley *et al.*, 2004). Furthermore, lithological and field investigations have revealed that one of the tills within the NSDF, the Walcott Diamicton (Lunkka, 1994), is the lateral equivalent of the Lowestoft Formation till, thus rendering the NSDF invalid as a stratigraphical unit (Hamblin *et al.,* 2000; Moorlock *et al.,* 2002; Lee *et al.*, 2004a). These findings have led to the development of a new glacial stratigraphy for the region (Table 1; Lee *et al.*, 2004a) and the proposition that these glacial deposits were predominantly British-sourced, deposited during a number of different glacial cycles throughout the Middle Pleistocene. This multi-stage glaciation model has been supported by the presence of erratics and armoured till-balls of the lowermost diamicton member of the NSDF within early Middle Pleistocene Bytham River deposits at Leet Hill [TM 384 926] suggesting the presence of pre-Anglian glaciation within eastern England (Lee *et al.*, 2004b).

GEOLOGICAL SETTING

The present study reports the findings of an investigation within Briton's Lane Quarry [TG 1700 4145] that is situated on the northern flank of the Cromer Ridge, 2 km southeast of Sheringham (Fig. 1). The quarry dissects a 39 m-thick sequence of the Briton's Lane Formation sand and gravel that rises to 100 m OD. These sands and

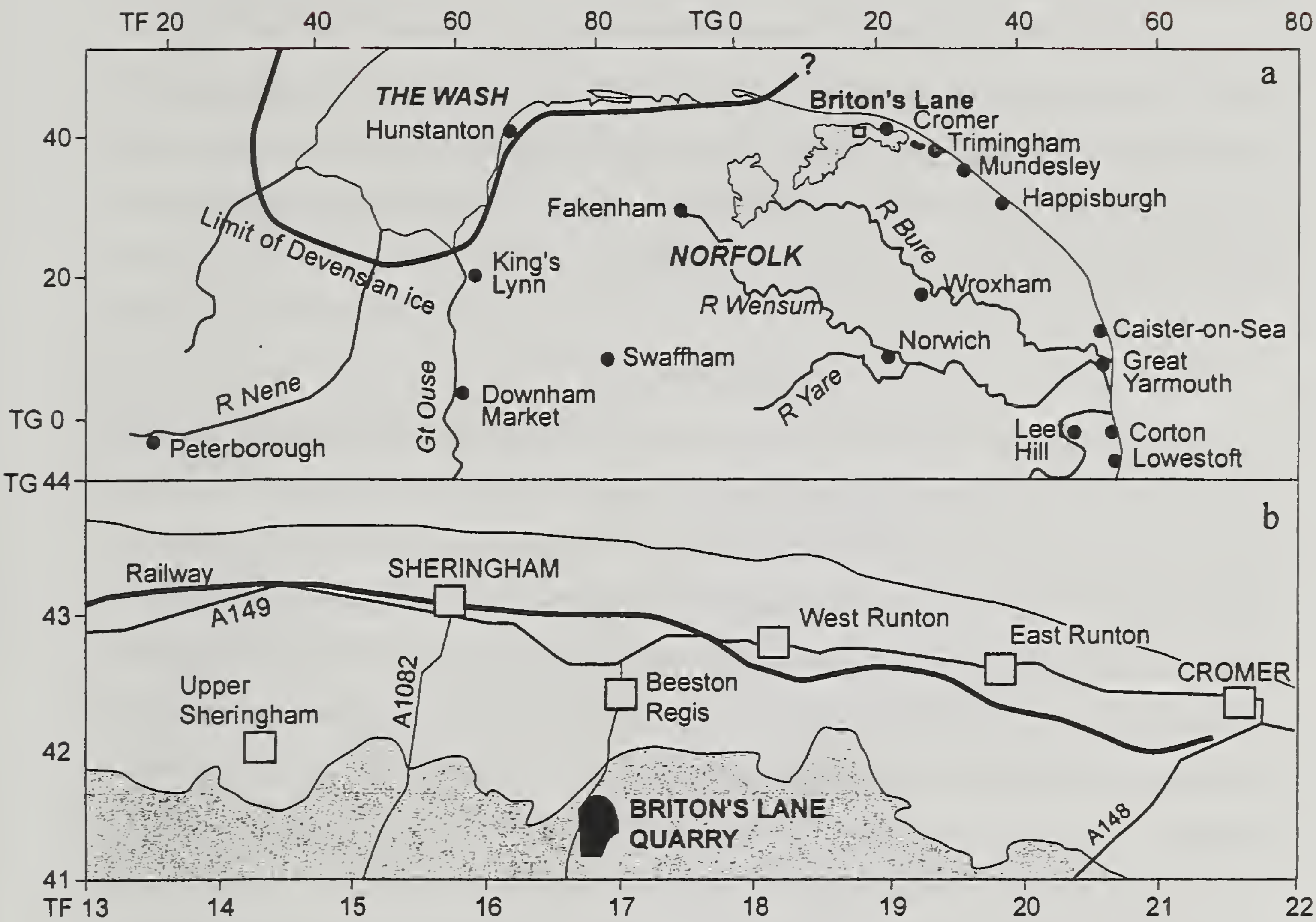


Fig. 1. a) Approximate position of the Cromer Ridge (grey tone = land over 60 m OD) and Briton's Lane Quarry. Scale given by 20 km national grid squares. b) Expanded map of study area showing the position of Briton's Lane Quarry on a 1 km grid square map.

Banham (1975)	**Lunkka (1994)**	**This paper (from Lee *et al.*, 2004a)**	
Lowestoft Till	Lowestoft Till		
		Britons Lane Sand and Gravel Member	*Briton's Lane Formation (formerly Overstrand Fmn)*
Third Cromer Till	Cromer Diamicton and Mundesley Diamicton	Bacton Green Till Member	*Sheringham Cliffs Formation (formerly Beeston Regis Fmn)*
Second Cromer Till	Walcott Diamicton	Walcott Till Member	*Lowestoft Formation*
First Cromer Till	Happisburgh Diamicton	Happisburgh Till Member and Corton Till Member	*Happisburgh Formation (formerly Corton Fmn)*

Table 1. Correlation of stratigraphic schemes of Banham (1975), Lunkka (1994) and the new glacial stratigraphy of Lee *et al.* (2004a). Note that the 2nd Cromer Till or Walcott Diamicton is now considered a lateral equivalent of the Lowestoft Till.

gravels can be traced over the northern flank of the ridge where they occur as a thick drape overlying multiple till sheets and glaciolacustrine sediments of the Lowestoft and Sheringham Cliffs Formation (Moorlock *et al.*, 2002; Lee *et al.*, 2004a). During February 2002, a British Geological Survey purpose-drilled borehole was taken through the base of the Briton's Lane Sand and Gravel at 62 m OD in order to investigate a continuous stratigraphical sequence through the thickest part of the Cromer Ridge and to test the number and provenance of ice advances into the region.

METHODOLOGY

The borehole was drilled with staff of the British Geological Survey (BSPM, RGC) and members of the Department of Geography at Royal Holloway University of London (SMP, JRL) in attendance. The borehole was drilled using the shell and auger percussion method and its elevation surveyed. Cohesive sediments were collected as core segments or undisturbed U100 (100 mm diameter coring tubes) samples, and bulk samples of non-cohesive sands and gravels were collected in polythene bags for later laboratory analysis. Accordingly, sedimentary structures were usually unrecognisable in non-cohesive sediments.

Selected quarry faces and borehole sections were logged using modified lithofacies schemes (Eyles *et al.*, 1983) and sedimentary texture described according to Moncrieff (1989). Sediment colour was defined using Munsell Colour charts. Particle-size analysis on the <2 mm size fraction was performed by wet and dry sieving with the <63 μm fraction determined using a Micromeritics Serigraph 5100 (Coakley & Syvitski, 1991). Calcium carbonate content determination was carried out on the <2 mm size fraction using the gasometric method (Gale & Hoare, 1991).

The clast lithological composition of the 8-16 mm and 4-8 mm size ranges has been quantitatively determined and the presence of any oversized erratic clasts noted in quarry faces. Heavy minerals have been analysed from the 63-125 μm sand fraction as a provenance and correlation aid (Catt & Penny, 1966; Madgett & Catt, 1978; Perrin *et al.*, 1979; Morton & Hallsworth, 1999) with opaque minerals expressed as a percentage of total mineralogy and non-opaque grains expressed as a percentage of total non-opaques. Allochthonous palynomorphs have also been identified and used as an additional indicator of provenance (Riding *et al.*, 1997; 2000; Moorlock *et al.*, 2000a; Lee *et al.*, 2002), and these have been categorised into groups of known stratigraphical age.

DESCRIPTION OF THE BOREHOLE AND QUARRY SECTIONS

The borehole penetrated four lithofacies units identified on the basis of sedimentary structure and lithological properties (Fig. 2). These consist of a lower shelly gravel facies (Lithofacies A) overlain by a 57 m-thick glaciogenic sequence comprising intercalated mud and diamicton facies (Lithofacies B), highly chalk-rich diamicton (Lithofacies C) and sandy diamicton (Lithofacies D). A 39 m-thick sequence of sand and gravel of the Briton's Lane Formation (Lithofacies E) overlies the diamictons and is exposed extensively in quarry-face sections (Fig. 3).

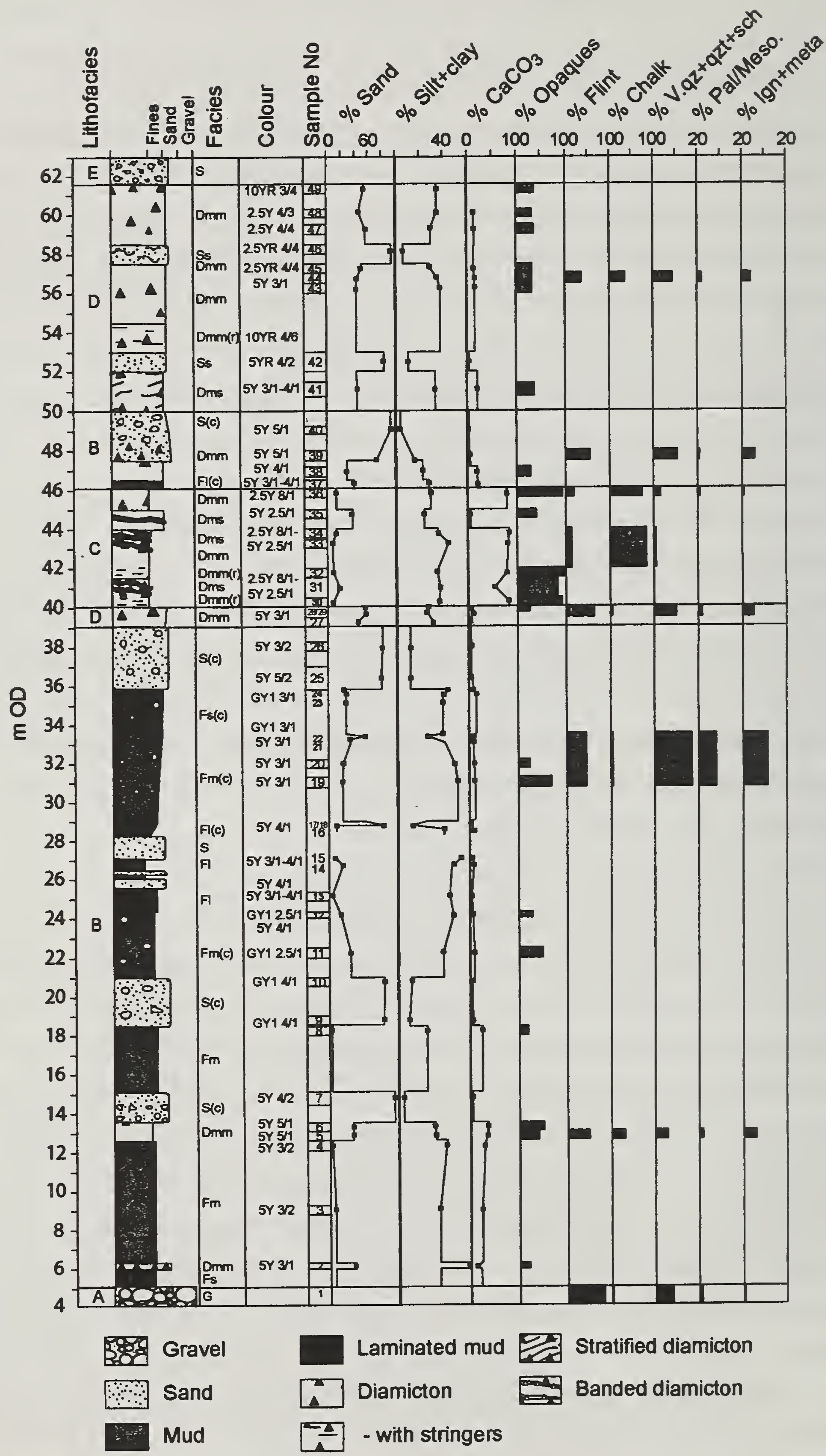
Lithofacies A (shelly gravel)

Lithofacies A forms the lowermost unit of the borehole, present between 4-5 m OD (Fig. 2). The lithofacies comprises a single m-thick unit of sandy gravel containing rounded to sub-angular large pebble to cobble clasts with a fine-grained sand matrix. Clasts are mainly composed of flint, chatter-marked flint and small proportions of white/colourless quartzose rocks (Table 2). Marine shells are common along with traces of Carboniferous, *Rhaxella* and Greensand chert, phosphatic glauconitic sandstone nodules and Old Red Sandstone. Small amounts of crystalline rocks present include basaltic porphyry and mica-schist.

Lithofacies B (mud and diamicton)

Lithofacies B comprises 38 m (total) of massive or laminated silts and muds, diamictons and muddy sands, present in the lower half of the borehole between 5-40 m OD with a second unit further up-core between 46–50 m OD. The lithofacies is dominated by dm to m-thick units of dark grey mud, sandy mud and silt which contain scattered (<0.2%) granules and small pebbles (Fig. 2). The muds are mostly massive to faintly-laminated, but well-laminated intervals occur in places displaying very fine-grained sand and chalky mud couplets. Sand units interdigitate with the muds and occur as m-thick beds of muddy or gravelly fine-grained sand to clast-rich sandy diamicton. Muddy diamicton units are also interbedded with the muds and have similar dark grey matrix colours and massive structure.

Clasts obtained from pebbly sand and muddy diamicton beds contain variable amounts of flint and chalk (Table 3) along with traces of phosphatic glauconitic sandstone nodules, coal, Jurassic sandstone, limestone and Devonian Old Red Sandstone.



Lithofacies
Fines
Sand
Gravel
Facies
Colour
Sample No
% Sand
% Silt+clay
% CaCO3
% Opaques
% Flint
% Chalk
% V.qz+qzt+sch
% Pal/Meso.
% Ign+meta
m OD
Gravel
Sand
Mud
Laminated mud
Diamicton
- with stringers
Stratified diamicton
Banded diamicton

			Dev.		Carb.			Triassic				Jurassic			Cretaceous							Cenozoic				Crystalline			
Sample	Height (m OD)	*n*	Old Red Sandstone	Total Devonian	Limestone+ironstone	Chert	Total Carboniferous	Vein quartz	Quartzite	Schorl	Total Triassic	Rhaxella chert	Sst+lmst+pyt+lst+shell	Total Jurassic	Black flint	White+brown flint	Glauconitic sandstone	Greensand chert	Chalk	Carstone + sst. + shell	Total Cretaceous	C-M flint	Shell+wood	Total Cenozoic	Total flint	Igneous	Metamorphic	Total crystalline	Unknown
Lithofacies A – shelly gravels (8-16 mm)																													
BL1	4.5	734	0.1	**0.1**	0.0	0.5	**0.5**	6.1	1.8	0.5	**8.4**	1.1	0.0	**1.1**	5.4	64.6	0.3	0.1	0.3	0.1	**70.8**	12.9	4.6	**17.8**	**83.0**	0.5	0.1	**0.7**	0.7
Lithofacies A – shelly gravels (4-8 mm)																													
BL1	4.5	527	0.0	**0.0**	0.0	0.6	**0.6**	8.7	2.1	0.8	**11.6**	0.6	0.0	**0.6**	6.5	56.4	0.2	0.0	0.0	0.0	**63.0**	1.3	19.5	**20.9**	**64.1**	1.9	0.2	**2.1**	1.3

Table 2. Clast lithological analysis of lithofacies A (4-8 mm and 8-16 mm fraction). Quartzose rocks are considered to be derived from the Triassic of central England (Rose *et al.*, 2001).

Fig. 2. (facing page) Lithostratigraphic log of lithofacies A to D (borehole sediments) with a graphical summary of particle size, calcium carbonate content, percentage opaque heavy minerals, and 4-8 mm clast lithology presented adjacent to the corresponding sample number. Facies codes: Dmm = Diamicton, matrix-supported, massive; Dmm(r) = with stringers; Dms = Diamicton, matrix-supported, stratified; Fm = Fines, massive; Fl = Fines, laminated; S = Sand, structure not preserved; Ss = with crude wavy bedding; G = Gravel, structure not preserved; (c) = with dispersed clasts.

Relatively abundant crystalline rocks (5.2-6.3%) include acid and basaltic porphyry, granite, vein quartz and schist. Heavy mineral contents also tend to vary within and between individual units although high proportions of epidote, amphibole and garnet are generally present (Table 4).

The mud and diamicton beds contain a distinctive palynoflora and organic residue with abundant wood fragments and plant tissues (Table 5). Abundant Quaternary palynomorphs are present along with small proportions of Palaeogene dinoflagellate cysts of predominately Ypresian (Early Eocene) age. Small levels of Carboniferous spores include inputs from a range of Carboniferous strata; *Auroraspora* cf. *macra* is from the Late Devonian (Famennian) to Early Carboniferous (Tournasian-early Viséan) (Clayton *et al.*, 1977; Clayton & Butterworth, 1984); *Endosporites globiformis* is typical of the Westphalian (Clayton & Butterworth, 1984) and *Tripartites trilinguis* of the Viséan-Namurian transition (Owens *et al.*, 1977). The Jurassic palynomorph content mainly consists of Mid Jurassic miospores including *Classopollis classoides* and *Perinopollenites elatoides*. Jurassic dinoflagellate cysts are sparse with *Cribroperidinium globatum* and *Gonyaulacysta jurassica* indicative of the Kimmeridgian. Traces of Late Cretaceous dinoflagellate cysts include *Cribroperidinium reticulatum*, *Cribroperidinium wetzelii*, *Hystrichosphaeropsis quasicribrata* and *Spongodinium delitiense* that are indicative of the Campanian-Maastrichtian transition (Herngreen *et al.*, 1996; Stover *et al.*, 1996; Roncaglia & Corradini, 1997; Schiøler *et al.*, 1997).

Lithofacies C (chalk-rich diamicton)

Chalk-rich diamicton occurs in the middle section of the borehole between 40-46 m OD. The facies comprises a highly calcareous, clast-rich diamicton with a white matrix colour and silt-rich matrix (Fig. 2). The diamicton is stratified with cm-thick, sharply bounded laminations or lenses of grey coloured muddy diamicton of similar lithology to lithofacies B. Clasts almost exclusively consist of chalk with small amounts of flint and quartzose rocks (Table 3). Traces of mudstone, Carboniferous limestone and dolerite are also present. The heavy mineral content of the facies is distinguished by a very high opaque mineral content (Table 4).

Three samples produced extremely rich palynofloras that are dominated by Late Cretaceous dinoflagellate cysts (Table 5). Key species comprise *Alisocysta circumtabulata*, *Cladopyxidium paucireticulatum*, *Isabelidinium cooksoniae*,

Table 3. Clast lithological analysis of borehole sediments (Lithofacies B to D) performed on the 4-8 mm size fraction and Briton's Lane Sand and Gravel (Lithofacies E). Note that quartzose lithologies and cherts in glacial deposits are considered to be reworked from Early to early-Middle Pleistocene sediments.

		D.	Carb.			PT	Jurassic			Cretaceous				Cenozoic						Crystalline			
Sample	*n*	ORS	Crystalline limestone	Coal	Carboniferous (total)	New Red Sandstone	Limestone+mudstone	Sst.+mica.sst.+calc.sst.	Jurassic (total)	Glauc. sst+imst.	White chalk	Flint	Cretaceous (total)	C.M. flint	V.qz.+qzt.+schorl .	Carb.+Rhax.+Greensand chert	Shell+wood	Cenozoic (total)	Total flint	Igneous	Metamorphic	Total crystalline	Unknown
Lithofacies E – Briton's Lane Sand and Gravel (6-16 mm)																							
BL-58	401	**0.2**	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.0	0.0	83.3	**83.3**	4.5	8.5	1.0	0.0	**14.0**	**87.8**	1.2	1.2	**2.4**	0.0
BL-57	490	**0.2**	0.0	0.0	**0.0**	0.0	0.0	0.6	**0.6**	0.0	0.0	79.3	**79.3**	7.6	10.0	1.4	0.0	**19.0**	**86.9**	0.6	0.2	**0.8**	0.0
BL-56	711	**0.1**	0.0	0.0	**0.0**	0.0	0.0	0.1	**0.1**	0.0	0.0	67.9	**67.9**	14.8	12.1	2.1	0.3	**29.3**	**82.7**	0.7	0.8	**1.5**	1.0
BL-55	630	**0.0**	0.0	0.0	**0.0**	0.0	0.0	0.6	**0.6**	0.0	0.0	74.8	**74.6**	8.9	11.3	1.4	0.0	**21.6**	**83.7**	1.4	0.8	**2.2**	0.8
BL-54	484	**0.2**	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.0	0.0	84.1	**84.1**	4.5	8.5	1.2	0.0	**14.2**	**88.6**	0.6	0.8	**1.4**	0.0
BL-53	640	**0.2**	0.0	0.0	**0.0**	0.0	0.0	0.3	**0.3**	0.0	0.0	75.6	**75.6**	10.3	8.8	1.7	0.2	**21.0**	**85.9**	0.6	1.4	**2.0**	0.9
BL-52	475	**0.0**	0.0	0.0	**0.0**	0.0	0.0	1.1	**1.1**	0.0	0.0	77.0	**77.0**	7.6	10.7	0.8	0.0	**19.1**	**84.6**	0.8	1.9	**2.7**	0.0
BL-51	711	**0.0**	0.0	0.0	**0.0**	0.1	0.0	0.0	**0.0**	0.0	0.0	72.7	**72.7**	10.8	13.1	1.1	0.0	**25.0**	**83.5**	1.5	0.6	**2.1**	0.0
BL-50	295	**0.0**	0.0	0.0	**0.0**	0.0	0.0	0.0	**0.0**	0.0	0.0	78.9	**78.9**	7.5	9.8	1.7	0.0	**19.0**	**86.4**	1.4	0.7	**2.1**	0.0
Lithofacies D – sandy diamicton (4-8 mm)																							
BL-44	221	**0.0**	0.0	0.0	**0.0**	**0.0**	0.5	1.4	**1.8**	0.0	35.7	38.0	**73.8**	0.0	9.5	3.6	2.3	**15.4**	**38.0**	3.6	0.9	**4.5**	4.5
Lithofacies C – chalk rich diamicton (4-6 mm)																							
BL-36	448	**0.0**	0.2	0.0	**0.2**	**0.0**	0.2	0.0	**0.2**	0.2	74.8	19.9	**94.9**	0.0	3.3	0.2	0.9	**4.5**	**19.9**	0.2	0.0	**0.2**	0.0
BL-32-34	195	**0.0**	0.0	0.0	**0.0**	**0.0**	0.0	0.0	**0.0**	0.0	84.6	13.8	**98.5**	0.0	1.0	0.0	0.5	**1.5**	**13.8**	0.0	0.0	**0.0**	0.0
Lithofacies B – mud and diamicton (4-8 mm)																							
BL-28,29	173	**0.0**	0.0	0.6	**0.6**	**0.0**	1.2	0.6	**1.7**	0.0	4.6	60.1	**64.7**	1.7	10.4	1.7	8.7	**22.5**	**61.8**	4.0	1.2	**5.2**	5.2
BL-5-6	192	**0.0**	0.0	0.0	**0.0**	**0.0**	1.0	0.0	**1.0**	0.0	30.7	49.5	**80.2**	1.0	5.7	1.0	2.6	**10.4**	**50.5**	5.2	0.5	**5.7**	2.6
BL-39	396	**0.3**	0.0	0.0	**0.0**	**0.0**	0.0	0.3	**0.3**	0.3	0.5	58.3	**59.1**	0.5	11.4	5.6	10.4	**27.8**	**58.8**	4.8	1.5	**6.3**	6.3

Sample	n total	Opaques (%)	Epidote Gp	Amphibole Gp	Tourmaline Gp	Pyroxene Gp	Zircon	Sphene	Garnet	Sillimanite	Kyanite	Staurolite	Rutile	Apatite*1	Chlorite	Glauconite	Others*2
Lithofacies E – Briton's Lane Sand and Gravel																	
BL-58	371	**78**	40	12	4	1	32	0	4	1	2	0	4	0	0	0	0
BL-57	440	**53**	19	22	5	2	22	0	24	0	1	1	1	1	0	0	0
BL-56	457	**58**	31	19	5	2	15	0	20	0	1	1	3	2	1	1	0
BL-54	407	**64**	33	18	7	2	14	0	19	0	1	1	3	0	0	0	1
BL-52	462	**36**	16	26	3	1	15	0	33	0	1	1	2	0	1	0	0
Lithofacies D – sandy diamicton																	
BL-49	528	**39**	30	32	5	0	4	3	13	0	0	1	2	5	4	0	0
BL-48	616	**32**	28	38	3	1	4	1	12	0	0	1	2	6	2	0	0
BL-47	736	**39**	35	32	1	1	5	2	17	0	0	0	0	5	2	0	0
BL-45	538	**33**	28	34	4	0	7	1	16	1	0	1	2	5	2	0	0
BL-44	485	**33**	27	34	4	4	4	1	16	0	0	1	1	6	2	0	1
BL-41	452	**41**	24	35	1	2	8	3	13	0	1	0	2	5	3	1	1
Lithofacies C – chalk-rich diamicton																	
BL-36	737	**95**	31	24	3	1	4	3	21	0	1	3	1	5	3	0	0
BL-32	793	**97**	30	21	3	0	8	2	26	2	3	0	3	1	2	0	0
BL-31	737	**82**	28	25	5	0	6	2	25	1	0	1	1	3	2	0	1
BL-30	746	**92**	34	32	3	2	8	1	15	0	0	2	1	2	0	0	0
Lithofacies B – mud and diamicton																	
Diamicton facies																	
BL-38	386	**34**	29	46	2	1	1	1	9	0	2	0	0	2	5	0	0
BL-35	558	**39**	30	30	4	0	3	3	15	0	0	1	1	7	5	0	0
BL-29	465	**25**	28	32	4	1	4	2	18	1	0	0	1	5	3	1	1
BL-2	359	**24**	29	37	4	1	4	3	13	0	0	1	1	2	4	0	0
BL-5	492	**43**	31	29	4	2	5	5	14	0	0	1	1	4	3	0	0
BL-6	516	**48**	22	32	3	3	9	2	19	0	1	1	1	4	1	1	0
Sand and mud facies																	
BL-20	637	**24**	31	27	3	2	6	2	17	0	0	2	2	4	2	0	1
BL-19	663	**19**	38	29	4	1	4	1	12	0	0	1	1	4	1	0	1
BL-12	628	**50**	21	45	3	1	2	4	17	0	0	0	1	3	2	0	1
BL-11	436	**28**	29	41	2	1	3	2	12	0	0	1	0	4	4	0	0
BL-7	614	**70**	26	22	6	2	10	2	24	2	0	1	0	5	1	0	0

Table 4. Heavy mineralogy of the Briton's Lane Quarry sedimentary facies. Analysis performed on 63-125μm fraction. Opaque minerals expressed as percentage of total mineralogy: non-opaque minerals are expressed as a percentage of total non-opaques.

Sample	Grains/slide	% Carboniferous mios.	% Permo-Trias mios.	% Jurassic miospores	% Jurassic d.cysts	% L. Cretaceous. mios.	% L. Cretaceous. d.cysts	% U. Cretaceous. d.cysts	% Palaeogene d.cysts	% Quaternary mios.	% Quaternary d.cysts	% Non-age diagnostic
Lithofacies D (sandy diamicton)												
BL-48	**2014**	20.1	0.1	26.8	4.4	-	-	1.5	0.5	2.1	2.8	**41.7**
BL-47	**1563**	16.0	-	26.5	10.4	-	-	1.2	0.6	1.3	0.5	**44.7**
BL-44	**1907**	11.9	-	20.2	2.0	-	-	4.4	1.4	3.4	1.1	**55.6**
Lithofacies C (chalk-rich diamicton)												
BL-36	**18813**	-	-	0.1	0.04	-	-	98.7	-	-	-	**1.2**
BL-31	**3664**	1.5	-	4.4	0.4	-	0.1	44.1	0.1	8.5	1.4	**39.5**
BL-30	**21879**	0.1	-	0.1	-	-	-	99.3	-	0.2	0.04	**0.4**
Lithofacies B (mud and diamicton)												
BL-35	**3871**	0.7	-	1.0	-	-	-	0.1	-	27.9	1.4	**68.9**
BL-29	**2906**	5.1	-	13.6	1.7	-	-	1.2	0.4	19.2	-	**58.8**
BL-20	**4686**	2.0	-	4.8	0.5	-	-	0.6	3.6	24.2	0.1	**64.2**
BL-19	**3205**	3.2	-	3.4	0.1	0.2	0.1	0.7	2.5	20.5	0.2	**69.1**

Table 5. Age-diagnostic palynomorph species levels within analysed diamicton samples. Species are grouped into categories of known stratigraphical age.

Neoeurysphaeridium glabrum, *Palaeotetradinium maastrichtiense*, and *Xenascus wetzelii* that are indicative of the Campanian-Maastrichtian transition. Trace proportions of Early Cretaceous forms include 3 specimens of the latest Jurassic-Early Cretaceous dinoflagellate *Gochteodinia villosa*. Traces of Jurassic palynomorphs are only present in the stratified units.

Lithofacies D (sandy diamicton)

Lithofacies D occurs near the top of the borehole and consists of a 9.5 m-thick sequence of dark yellowish brown to very dark grey coloured, clast-poor diamicton with a consistent sandy texture and moderate matrix carbonate content (Fig. 2). The diamicton units are clast-poor (*c.* 3-5%) and either have a massive structure or contain chalky stringers. Some units are intensely banded with mm-thick horizontal and sharply bounded laminations of chalky, dark-grey coloured diamicton and several m-thick bodies of yellowish brown coloured sand are interbedded within the sequence.

Flint and chalk clasts are the most common lithological constituent with small amounts of quartzose rocks (Table 3). Small amounts of Jurassic sandstone and mudstone are present. Crystalline rocks include acid porphyry, granite, vein quartz, dolerite, quartz- and quartz-mica schist. The facies also has a consistent heavy mineral content with moderate proportions of opaque minerals and high proportions of epidote and amphibole (Table 4).

Three samples produced a diverse palynomorph assemblage characterised by abundant Carboniferous and Jurassic forms (Table 5). The Carboniferous spores indicate input from a range of Carboniferous strata; *Tripartites trilinguis* is characteristic of the Viséan-Namurian transition (Owens *et al.*, 1977) and *Reticulatisporites reticulatus* is typical of the Westphalian (Clayton *et al.*, 1977; Clayton & Butterworth, 1984). The high Jurassic miospore content includes *Cerebropollenites macroverrucosus, Chasmatosporites* spp., *Classopollis classoides* and *Perinopollenites elatoides* that are indicative of the Mid-Late Jurassic (Riding *et al.*, 1991). Significant proportions of Jurassic microplankton include key species such as *Halosphaeropsis liassica, Mancodinium semitabulatum*, *Nannoceratopsis deflandrei* subsp. *deflandrei* and *Nannoceratopsis deflandrei* subsp. *senex*. This association is indicative of the Early Jurassic (early Toarcian) (Riding *et al.*, 1999; Bucefalo Palliani & Riding, 2000). Small numbers of *Liasidium variabile* are indicative of an input from Upper Sinemurian strata (Bucefalo Palliani & Riding, 2000) and small proportions of Kimmeridgian Stage dinoflagellate cysts are also present. Relatively low proportions of Late Cretaceous dinoflagellate cysts include species indicative of the Campanian-Maastrichtian transition based on the occurrences of *Hystrichosphaeropsis quasiscribrata*, *Microdinium* spp., and *Spongodinium delitiense*. Palaeogene dinoflagellate cysts indicate input from the Early-Mid Eocene (Ypresian to Lutetian).

Lithofacies E (Briton's Lane Sand and Gravel)

A 39 m-thick sequence of horizontally bedded sand and gravel overlies lithofacies D at 62 m OD and is exposed extensively within the quarry (Fig. 3). The sequence is dominated by massive dm-thick gravel sheets alternating with horizontally bedded sands. The gravels are mostly clast-supported and poorly sorted with large pebble to cobble sized clasts. Erosional lower contacts are common and normal or reverse grading is occasionally present. The sand interbeds form subordinate 4-15 cm-thick beds that frequently pinch-out laterally and display normal grading from horizontally bedded

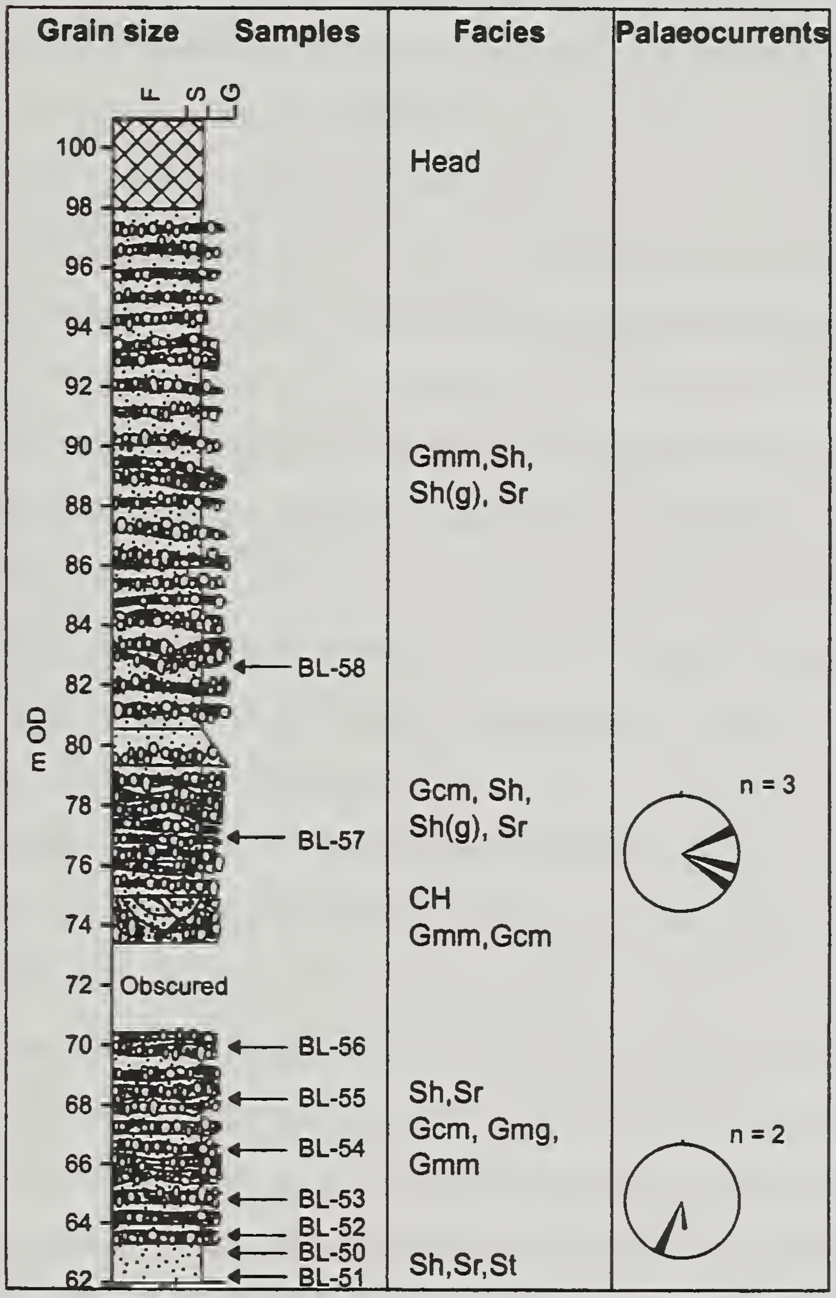


Fig. 3. Sedimentary log and sampling locations of lithofacies E (Briton's Lane Sand and Gravel) with results of palaeocurrent measurements from bedding planes. Facies codes: Gmm = Gravel, matrix-supported, massive; Gcm = Gravel, clast-supported, massive; Sh = Sand, horizontally bedded; Sr = Sand, ripples; St = Sand, trough-cross bedding; (g) graded; CH = channel-fill structure.

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medium-grained sand to rippled fine-grained sand. Palaeocurrent measurements from rippled sand (Sr) units indicate flow towards the south (Fig. 3). Macrostructures are rare and comprise 3 m-wide channel-fill structures with clast-supported gravel fills. Smaller, 10 – 30 cm wide channel-fill structures occur more commonly where they rest on gravel sheet surfaces and display fining-up fills from coarse-grained to fine-grained silty sand.

The sands and gravels contain very high proportions of flint and chatter-marked flint with small amounts of quartzose rocks and traces of Greensand chert, *Rhaxella* chert and Carboniferous chert (Table 3). Other indicator lithologies include traces of Jurassic sandstone along with bright red and dark purple coloured sandstones. A diverse range of crystalline rocks (1.4-2.8%) includes acid and basaltic porphyry, granite, quartz dolerite, schists, with traces of meta-quartzite, baked sandstone, and schistose grit. Low proportions of amphibole and high proportions of zircon distinguish the sands and gravels from the heavy mineral content present in other lithofacies (Table 4).

INTERPRETATION OF LITHOFACIES UNITS

Lithofacies A – Mundesley Member (Wroxham Crag Formation)

High proportions of chatter-marked flint and marine shell with small amounts of quartzose lithologies are typical of the Mundesley Member of the Wroxham Crag Formation (Rose *et al.*, 2001). This deposit is attributed to an early-Middle Pleistocene shallow-marine environment influenced by input from the Thames and Ancaster River systems. Trace amounts of igneous and metamorphic clasts are suggested to reflect early-Middle Pleistocene upland glaciation and an input of erratics into lowland river systems.

Lithofacies B – Ivy Farm Laminated Silts (Sheringham Cliffs Formation)

The thickness of the mud and silt beds along with the stratigraphical position underlying sandy and chalk-rich diamictons suggests that this lithofacies is equivalent to glaciolacustrine deposits termed the Lower Clay Bed (Hart, 1990), Mundesley Diamicton (Lunkka, 1994) or Ivy Farm Laminated Silt (Lee *et al.*, 2004a) that crop out along coastal sections between Trimingham and Sheringham. The thick mud beds were probably deposited from suspension with scattered pebbles derived from iceberg rafting. Laminated intervals with sand-mud couplets and some gradational contacts represent rhythmite structures, probably deposited by distal turbidity currents (Smith & Ashley, 1985). The poorly sorted and mud-rich texture of the sand units and the frequent inter-bedding with massive and laminated mud units suggests that deposition may have occurred subaqueously, perhaps by sediment flow processes (Middleton & Hampton, 1976). Large textural and mineralogical variations in the massive muddy diamicton interbeds are consistent with sorting effects occurring during waterlain deposition. The massive structure may have resulted from the rapid rain-out of suspended muds and ice-

rafted debris (e.g. Eyles *et al.*, 1985; Gilbert, 1990) or by debris flow processes (e.g. Kurtz & Anderson, 1979; Eyles, 1987).

Lithofacies C – Weybourne Town Till (Sheringham Cliffs Formation)

This chalk-rich diamicton facies is characterised by its extremely high Cretaceous chalk content, abundant Campanian-Maastrichtian palynomorphs, and a high opaque heavy mineral content. These properties are typical of the Weybourne Town Till Member that crops out at nearby localities such as Weybourne and Beeston (Table 6) (Pawley *et al.*, 2004; Lee *et al.*, 2004a). The stratification of the facies with laminations and lenses of grey coloured, muddy diamicton suggests that deposition occurred subglacially with underlying muds and muddy diamictons of Lithofacies B being incorporated and sheared out within the till (Hart & Boulton, 1991b).

Lithofacies D – Bacton Green Till (Sheringham Cliffs Formation)

This facies is a brown to grey coloured, sandy and stratified diamicton which has matrix carbonate content and heavy mineral composition typical of the Bacton Green Till Member of the Sheringham Cliffs Formation (Table 6), previously referred to as the Third Cromer Till (Perrin *et al.*, 1979; Lunkka, 1994; Pawley *et al.*, 2004; Lee *et al.*, 2004a). This facies is thought to be a glaciotectonite with chalky stringers and stratified units formed by the subglacial deformation of different sediment types (Hart & Boulton, 1991b; Roberts & Hart, 2005).

Lithofacies E – Briton's Lane Sand and Gravel (Briton's Lane Formation)

Lithofacies E represents the type-site for glaciofluvial deposits that drape the northern flank of the Cromer Ridge. The clast-supported gravel sheets with erosive lower contacts represent clast-by-clast deposition from traction (Miall, 1977, 1985). The sand interbeds record plane-bed flow over the gravel sheets with the fining-up tendencies and occasional transitions from flat-bed into ripple-drift bedding reflecting declining flow velocities (Smith, 1985). The absence of cross-stratification indicates that water depths remained generally shallow with deposition occurring as sheets in virtually unconfined channels. Minor gravel-filled channel forms may represent incision between bar surfaces. The smaller and more common sand-filled channels that rest on the gravel sheet surfaces are likely to represent the infill of small chutes developed on emerging bar surfaces. This

Table 6. Summary of the quantified lithological characteristics of several major till lithofacies present in eastern England and comparative lithological summary of lithofacies B.

				Sheringham Cliffs Formation				
	Happisburgh Till *1	Walcott Till *1	Lowestoft Till *1	Third Cromer Till *2	Bacton Green Till *1	Weybourne Town Till *2	Lithofacies C (chalk-rich till)	Lithofacies D (sandy till)
Munsell Colour	5Y 4/1 - 10YR 4/1	2.5Y 4/1 - 2.5Y 5/1	2.5Y 7/2 - 10YR 3/1	10YR 4/6 - 10YR 5/2	2.5YR 5/4 - 10YR 4/1	2.5Y 7/4	2.5Y 8/1	10YR 3/4 - 2.5Y 4/3
	Dark Grey	Dark grey - grey	Light grey - very dark grey	Dark yellowish brown - greyish brown	Reddish brown - dark grey	Pale yellow	White	Dark yellowish brown/olive
% Sand	43.9-57.2 (**50.7**)	22.6-38.8 (**30.0**)	6.5-10.1 (**12.0**)	42.8-46.9 (**45.0**)	46.4-69.2 (**56.7**)	18.9-38.6 (**31.6**)	7.7-12.3 (**9.0**)	43.2-56.1 (**49.0**)
% Silt	17.1-32.9 (**26.0**)	19.0-60.2 (**31.1**)	19.9-30.4 (**22.3**)	20.4-26.9 (**23.5**)	14.9-31.8 (**20.2**)	28.4-49.6 (**45.9**)	49.5-59.3 (**56.1**)	11.9-21.9 (**18.4**)
% Clay	20.0-33.0 (**23.4**)	14.3-45.3 (**38.5**)	56.5-69.8 (**65.7**)	29.9-4.1 (**31.4**)	14.6-37.3 (**23.2**)	13.1-52.5 (**22.4**)	28.4-42.7 (**34.9**)	28.8-36.7 (**32.6**)
% CaCO3	10.2-14.3 (**12.1**)	20.9-42.5 (**33.9**)	26.4-50.4 (**34.9**)	9-14 (**12.2**)	1.2-19.1 (**11.1**)	63.1-73.9 (**68.7**)	78.6-83.0 (**80.6**)	0.4-16.7 (**14.8**)
% Opaques	28.8 ± 2.3	36.7 ± 3.3	55.8 ± 4.0	26.8 ± 0.1	30.0 ± 3.1	40.2 ± 5.0	94.0 ± 3.0	34.8 ± 3.2
% Amphibole	40.2 ± 1.5	38.3 ± 3.3	27.7 ± 2.1	29.8 ± 3.2	42.3 ± 5.2	38.0 ± 8.6	30.1 ± 10.4	33.5 ± 2.9
% Epidote	23.7 ± 2.8	19.4 ± 2.0	17.0 ± 2.6	21.0 ± 0.8	22.8 ± 4.6	18.7 ± 3.1	16.0 ± 9.2	29.3 ± 2.7
% Garnet	15.6 ± 2.1	17.8 ± 4.5	17.8 ± 4.5	19.9 ± 2.6	17.4 ± 3.5	23.3 ± 7.2	15.7 ± 4.8	14.8 ± 2.1
% Zircon	4.9 ± 1.5	5.3 ± 1.7	8.1 ± 1.6	6.4 ± 0.4	5.3 ± 1.3	7.9 ± 2.8	6.1 ± 0.1	4.8 ± 1.1
% Apatite	2.7 ± 0.6	6.2 ± 1.0	16.4 ± 6.2	0.9 ± 0.1	1.6 ± 0.7	3.8 ± 1.8	11.9 ± 13.5	5.2 ± 0.5
% Mica	1.5 ± 0.8	4.2 ± 2.4	2.3 ± 1.4	6.2 ± 3.4	2.2 ± 1.0	1.1 ± 0.9	6.8 ± 1.2	2.6 ± 1.2
% Tourmaline	4.0 ± 1.0	3.3 ± 1.1	4.4 ± 1.0	5.5 ± 0.4	3.8 ± 1.4	2.8 ± 1.2	6.1 ± 6.1	3.5 ± 1.1
% Pyroxene	3.4 ± 1.5	1.6 ± 0.7	1.8 ± 0.4	2.9 ± 2.0	1.9 ± 0.2	1.1 ± 0.6	1.4 ± 2.4	1.4 ± 1.4
% Other	4.0 ± 0.4	5.7 ± 0.8	4.7 ± 0.9	7.5 ± 0.6	3.8 ± 0.7	2.5 ± 1.3	5.8 ± 1.0	4.9 ± 0.7

*1 Lee *et al* (2004a)
*2 Pawley *et al* (2004)

style of sedimentation is similar to ice-proximal deposition occurring on a waterlain dominated ice marginal fan (Boothroyd & Ashley, 1975; Krzyszkowski & Zieliński, 2002) and is consistent with the geological setting of the Briton's Lane Formation at this site, being situated at the northern, ice-proximal, margin of the Cromer Ridge.

PROVENANCE AND ICE-FLOW DIRECTIONS

Provenance of the Ivy Farm Laminated Silts

The muds and diamictons have a distinctive lithology characterised by locally (Cenozoic) derived clasts and palynomorphs. The abundance of wood fragments, plant tissues and Quaternary palynomorphs indicates that organic-rich deposits, perhaps equivalent to the West Runton Freshwater Bed were eroded and re-deposited in the lake bottom sediments. Chalk and flint clasts along with Cretaceous palynomorphs indicative of the local Campanian age Chalk Group and Early Eocene age dinoflagellate cysts support that large amounts of sediment was reworked from the area around the western North Sea Basin. The small proportions of Carboniferous spores indicate that a wide range of ages throughout the Carboniferous were also incorporated into this facies from the Northumberland-Durham area, north-east England and/or southern Scotland. The main source of Jurassic material appears to be the Mid Jurassic strata of the Yorkshire Basin and/or the East Midlands Shelf with a very limited input of Kimmeridgian dinoflagellate cysts from the Wash area. The lithological and palynomorph assemblages is best explained by the flow-path of a British based ice sheet that traversed Carboniferous to Pleistocene strata from central Scotland to north-east and eastern England.

Provenance of the Weybourne Town Till

The high levels of chalk and palynomorphs of Campanian to Maastrichtian age denote intense erosion of local Cretaceous Upper Chalk in north Norfolk. Small proportions of Jurassic miospores and Kimmeridgian dinoflagellate cysts in stratified horizons are likely to have been reworked from underlying facies. However, trace levels of the Late Jurassic-Early Cretaceous dinoflagellate *Gochteodinia villosa* indicate possible input from the Sandringham Sands and equivalents in West Norfolk and the Fenland region. Extremely high levels of opaque minerals may also support the erosion of Lower Cretaceous, iron-cemented sediments. This lithological assemblage is best explained by ice-flow from the west, moving across Lower Cretaceous and Chalk Group bedrock.

Provenance of the Bacton Green Till

The sandy diamicton facies contains abundant Cenozoic and Cretaceous clast lithologies with a significant component of Jurassic and Carboniferous clasts and high levels of Carboniferous and Jurassic palynomorphs. The presence of Jurassic sandstone, limestone and abundant Jurassic palynomorphs with terrestrial miospores of mostly Early to Mid-Late Jurassic age indicates that the Yorkshire Basin or East Midlands Shelf is the dominant source. Specifically, Sinemurian marine microplankton have a source in the Redcar Mudstone Formation of north-east England (Bucefalo Palliani & Riding, 2000) or the Brant Mudstone Formation of the East Midlands Shelf. Carboniferous palynomorphs indicate the erosion of a range of Carboniferous strata and could only be derived from the Northumberland-Durham area of north-east England or from southern Scotland as no Carboniferous rocks are exposed in the southern North Sea (Cameron *et al.*, 1992) or southwest Norway. The Old Red Sandstones, igneous erratics and low-grade metamorphic rocks are consistent with a Central Scotland source area (Cameron & Stephenson, 1985).

Provenance of the Briton's Lane Sand and Gravel

The large proportions of flint and chatter-marked flint with smaller proportions of quartzose material indicate substantial reworking of Cenozoic sediments in north Norfolk or the North Sea Basin. The small amounts of Jurassic sandstone may be derived from the East Midlands Shelf and the trace amounts of bright red sandstone and dark red/purple sandstone are likely to be derived from Permo-Trias and Devonian bedrock outcrops in northern England and central Scotland. The low amphibole content and high proportions of zircon possibly reflect the destruction of the physically weak mineral types during energetic glaciofluvial transport and the concentration of hydraulically heavy minerals in coarser-grained beds. A feature of the Briton's Lane Sand and Gravel is the relatively abundant crystalline erratic content which includes clasts Scandinavian provenance. These include trace amounts of rhomb porphyry recorded here and at Weybourne (Moorlock *et al.*, 2000b; Pawley *et al.*, 2004). However, no Scandinavian clasts were found in this study where the erratic assemblage of Mesozoic and Palaeozoic sandstones, igneous (acid and basic porphyry, granite, basalt, quartz dolerite) and low-grade metamorphic rocks (schist, garnet-mica schist, baked sandstone and schistose grit) is of a typically British provenance (Lee *et al.*, 2002).

DISCUSSION

Sedimentary environments

The glaciolacustrine deposits at the base of the succession are consistent with existence of a large glaciolacustrine basin between Trimingham and Sheringham (Hart & Boulton, 1991a; Lunkka, 1994; Lee *et al.*, 2004a). These glaciolacustrine deposits have been overridden by ice advances depositing the Bacton Green Till and Weybourne Town Till. The differing provenance and reconstructed ice-flow directions of these tills suggest that they represent two separate ice advances instead of reflecting the subglacial deformation of differing sediments during a single advance. The stratigraphical position of the Weybourne Town Till which is overlain by Bacton Green Till at Briton's Lane is in contrast to sites such as Weybourne (Fish *et al.*, 2000; Lee *et al.*, 2004a; Pawley *et al.*, 2004), Trimingham (Lunkka, 1994) and other localities in northwest Norfolk where the Weybourne Town Till overlies the Bacton Green Till. It is suggested that this inversion of the stratigraphy seen in the borehole and repetition of Lithofacies B probably reflects glaciotectonic deformation of the sequence. Finally, the Briton's Lane Sand and Gravel was deposited over the site as a large ice-marginal outwash fan. This facies was deposited as a thick drape of sediment following the proglacial deformation of underlying sediments (Lee *et al.*, 2004a).

Provenance of the former NSDF tills

The lithological evidence from Briton's Lane further challenges the view that Scandinavian tills and outwash sediments forming the Cromer Ridge were deposited by the retreat of a single Scandinavian-based ice sheet. Instead, the palynomorph and clast content of the tills record British-based ice-flow paths, with separate ice advances moving southwards along the western margin of the North Sea Basin or eastwards across the chalk escarpment and west Norfolk. The absence of older Palaeogene forms and the presence of Carboniferous palynomorphs demonstrate that ice could not have flowed across the southern North Sea Basin from Scandinavia. The presence of very rare Scandinavian lithologies reported in tills of unequivocally British-origin (Lee *et al.*, 2005; Hoare & Connell, 2005) does not challenge a British-provenance for these tills but does suggest that trace amounts of Scandinavian rock can be reworked by British-based ice from the southern North Sea Basin.

Provenance and correlation of the Briton's Lane Formation

The Briton's Lane Formation is known to contain a mixed clast assemblage including clasts of both British and Scandinavian provenance. On the basis that Scandinavian erratics appeared to be concentrated in gravels at Briton's Lane, Hamblin *et al.* (2000) attributed the Briton's Lane Formation to outwash from a Scandinavian ice depositing the Basement Till in east Yorkshire and Welton Till in Lincolnshire (Catt & Penny, 1966; Alabaster & Straw, 1976; Madgett & Catt, 1978). The Basement Till possibly represents evidence for an MIS-6 glaciation as it is thought to underlie the Ipswichian (MIS-5e) raised beach at Sewerby (Catt & Penny, 1966; Madgett & Catt, 1978; Bateman & Catt, 1996). Consequently, a number of authors have inferred that the Cromer Ridge represents an MIS-6 ice-limit (Boulton *et al.*, 1984; Hamblin *et al.*, 2000; Clark *et al.*, 2004). This has been refuted on the basis of pollen-assemblage biostratigraphy (Hart & Peglar, 1990; Banham *et al.*, 2001) and the chronology of this event is the subject of current research. However, recent finds of reworked Scandinavian rocks in British-deposited tills suggest that Scandinavian rocks are not unique to the Briton's Lane Formation and may be reworked from the North Sea Basin. The presence of rare Scandinavian rocks therefore does not unequivocally support a correlation between the east Yorkshire Basement Till and the Briton's Lane Formation.

CONCLUSIONS

1. The Briton's Lane quarry shows the northwest flank of the Cromer Ridge at this location to consist of four glaciogenic units overlying Early to early-Middle Pleistocene Wroxham Crag Formation sediments.
2. Glaciolacustrine deposits support evidence for the existence of a large ice-dammed lake prior to the construction of the Cromer Ridge.
3. These sediments are overlain by two tills correlated to the Bacton Green and Weybourne Town Tills. The tills and glaciolacustrine sediments were deposited by at least two separate British-based ice advances.
4. The Briton's Lane Sand and Gravel represents a thick drape of outwash deposited following the construction of the Cromer Ridge. The deposit contains rare Scandinavian clasts that have possibly been reworked from the North Sea Basin.

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DISCUSSION

THE FIRST APPEARANCE OF SCANDINAVIAN INDICATORS IN EAST ANGLIA'S GLACIAL RECORD - DISCUSSION

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INTRODUCTION

We were interested to read the article by Hoare & Connell (2005) in Bulletin 54, and are pleased that our paper (Lee *et al.*, 2004a) in the previous Bulletin has promoted active debate and discussion. The issue of Scandinavian erratic clasts within the glacial deposits of Norfolk has important implications for not just the glacial history of eastern England, but for the British Isles and North West Europe as a whole.

We do feel, however, that in several instances, the criticisms of our work by Hoare and Connell are invalid or erroneous as they have either misunderstood or misrepresented several important issues that we have presented and we consider it necessary to respond to and clarify each of these in turn.

THE DEVELOPMENT OF SCIENTIFIC IDEAS WITHIN THE BGS-RHUL RESEARCH GROUP

As Hoare and Connell point out, many of the earlier publications of the BGS-RHUL research group support the hypothesis that elements of the 'North Sea Drift' group of sediments contain *in situ* Scandinavian erratics. At this time, the research group had not examined the provenance of these sediments systematically and therefore they accepted the thoughts and writings of other workers who argued that Scandinavian erratics such as rhomb porphyry and larvikite were common (Bowen *et al.*, 1986; Ehlers *et al.*, 1991) and "...[could be] found at all exposures of North Sea Drift Cromer Tills..." (Ehlers & Gibbard, 1991, p. 18). It became apparent however, that despite several thousand days of fieldwork experience in northern East Anglia between the members of the research

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group, none of us had seen *in situ* rhomb porphyry or larvikite within any of the tills. Following a full review and evaluation of the literature and available evidence we undertook, from 2001 onwards, a systematic investigation of the lithology and provenance of the tills and outwash deposits to test the traditionally accepted hypothesis that these tills were of Scandinavian provenance. The evolution and development of our scientific ideas since this time are based upon the data derived from these new investigations and are reflected within later publications.

OUR REJECTION OF 180 YEARS OF GEOLOGICAL REPORTING

Hoare and Connell accuse us of rejecting 180 years of geological reporting of Scandinavian erratics in East Anglia without making any attempt to evaluate this information. This is incorrect, we most certainly *have* evaluated the papers referring to the presence of Scandinavian erratics in East Anglia, but have generally found them wanting as we outline below. We have rejected most of these papers on the grounds of their uncertainty, just as palaeontologists would have done with fossils of uncertain identity or unproven provenance. Most of the references cited by Hoare and Connell do not identify specific sites, or stratigraphic levels, or are general review-type papers that refer to other researchers' work which, unfortunately, all too often perpetuate and give further credence to misinformation.

In order to rebuff the charges made by Hoare and Connell, we discuss below each of the references cited by them on page 4 of their paper as confirming the presence of Scandinavian indicators in the earliest East Anglian glacial sediments. We hope that this will also provide a useful review of an important topic.

Buckland (1823). Hoare and Connell state that 'Erratics from Norwegian sources were first noted in the oldest glacial sediments of East Anglia by Buckland (1823)'. In this book, Buckland (p. 192) mentions the presence of bluish clays throughout much of eastern England from Newcastle to Essex. He noted that the clays contain pebbles of two classes, one composed of 'the wreck of the adjacent inland districts of England', the other composed of 'large blocks and pebbles of many varieties of primitive and transition rocks which do not occur in England and which could only be accounted for by supposing them to have been drifted from the nearest continental strata of Norway'. Buckland, of course, believed that all these deposits had been deposited by 'a force of water' rather than ice, and thus his interpretation was somewhat restricted. Nowhere in his account does Buckland actually state that he found Norwegian erratic clasts in the oldest glacial sediments of East Anglia. Indeed, the clays containing far travelled clasts that he refers to in Lincolnshire and Yorkshire are likely to be younger

than the oldest glacial deposits in East Anglia.

Trimmer (1851, 1858). His 1851 work (p. 21) briefly mentions 'Scandinavian' erratics in the 'Lower Glacial Erratics of Norfolk'. As he failed to mention the presence of erratic clasts from northern England and Scotland, which are common in these deposits, it seems very likely that he misidentified Scottish material as Scandinavian, and his conclusions must, therefore, be open to question. In his subsequent paper, Trimmer (1858, p. 171) describes the lower boulder clay at Gorlston, near Great Yarmouth as 'the tailing-off of that so well known for its blocks of Scandinavian origin, and which extends over the north of Europe and into the eastern side of England'. As with his 1851 paper, Trimmer gives no information on the types of 'Scandinavian' materials thought to be present. Moreover, like Buckland, he miscorrelates the lower till in Yorkshire, which contains relatively common Scandinavian erratics, with the lower till in Norfolk.

Sherborne (1887). The account of Sherborne (1887, p. 331) is restricted to a single paragraph in which he notes the presence of a clast of 'Rhomben-Porphyr' from the 'Cromer Boulder-Drift' at Runton. Recent work by one of us at Runton has confirmed the presence of the Briton's Lane Sand and Gravel Member (BLSG) (Lee, 2003) which does contain Scandinavian lithologies (Moorlock *et al.*, 2000b; Lee *et al.*, 2004a; Pawley *et al.*, 2004), so it is not unexpected that Sherborne found rhomb porphyry in the cliffs at this locality.

Kendall (1899, 1905). Certainly, as Hoare and Connell state, Kendall (1899) and his co-members on the Committee for Erratic Blocks of the British Isles, made great effort in trying to correlate erratic clasts found in eastern England with bedrock outcrops in Norway. However, it would appear that the samples referred to in Kendall's 1899 paper were collected by J.W. Stather and T. Sheppard who both worked north of The Wash in Yorkshire. The samples were thus presumably from the 'Basement Till' of Yorkshire although it cannot be discounted that they were examining younger tills deposited during the Last Glacial Maximum. It is interesting to note that in a more recent report by the Committee (Kendall, 1905), a number of erratics from the beach at Cromer were identified by two Swedish geologists as having their provenance in Sweden rather than Norway.

Boswell (1914, 1916). Boswell (1914, p. 125) states that '...it is well known that the Lower Glacial Beds of the coast and inland sections of Norfolk are especially characterised by the presence of boulders of igneous rocks, some of which are Scandinavian'. In his subsequent paper (1916) he states that 'the relative abundance of igneous rocks, and certainly the presence of Scandinavian types, in any section would be

good evidence of the North Sea Drift'. Boswell relies on earlier descriptions and provides no new information on the type, locality or stratigraphic position of any Scandinavian rock-types present.

Harmer (1928). This classic work provides much interesting information. On page 90 Harmer states 'The North Sea Drift is especially characterised, however, as at Corton, by the not infrequent occurrence of igneous boulders, by far the most common being of dolerite, the exact derivation of which has not be ascertained, but which no doubt came with the rest of the Lower Glacial detritus, from the North Sea ......They [boulders] are plentifully distributed along the road-side in the Cromer district, having been, no doubt, carted from the beach.' He records in a footnote that many erratic boulders in the village of Cley have been brought from the beach at Sheringham within living memory. Harmer does make reference (p. 91) to finding a small block of rhomb-porphyry in the 'North Sea Drift of the Norwich district' but does not refer to a specific locality or stratigraphic horizon. The fact that he refers specifically to this find suggests that the occurrence of this rock type is very uncommon.

Solomon (1932). Solomon (1932, p. 245) records that the lowermost till in north-east East Anglia contains 'some igneous rocks – both Scottish and Scandinavian have been recorded'. Later, on page 263, he mentions that 'all inland pits [in the Norwich Brickearth] have yielded Scandinavian erratics'. In neither instance does he give any further information about the specific types present nor indeed whether he actually found the erratics himself, or is simply reiterating the conclusions of others. Furthermore, Solomon states that the Cromer Ridge Gravels (Briton's Lane Sand and Gravel Member (BLSG), and glaciotectonized facies of earlier glacial units) have not yielded any distinctive erratics, which, in the case of the BLSG conflicts with our own work (Moorlock *et al.*, 2000b; Lee *et al.*, 2004a; Pawley *et al.*, 2004).

Bridge & Hopson (1985); Hopson & Bridge (1987). These publications, which relate to the Waveney valley, were published at a time when it was generally assumed that the deposits of the 'North Sea Drift' were derived from Scandinavian ice (Perrin *et al.*, 1979 – see Appendix in this for review of these deposits). Bridge and Hopson thus attributed the igneous clasts that they found in the Leet Hill Sand and Gravel Member to a Scandinavian provenance. On reflection, Bridge and Hopson (personal communication, February 2005), now consider that the purple feldspar porphyry and other igneous lithologies that they recorded could have been of Scottish rather than of Scandinavian provenance. This is our experience also (Rose *et al.*, 2000; Lee *et al.*, 2004b), and it should be noted that Carboniferous limestone from northern England and/ or Central Scotland has been found along with igneous rocks that include porphyries

derived from Devonian and Carboniferous outcrops in Central Scotland, again confirming their British provenance.

Ehlers et al. (1991). On page 223, Ehlers *et al.* mention that the '.....Cromer Tills contain ...about 1% of far-travelled erratics, amongst which some Norwegian indicator rocks occur (rhomb porphyries and larvikites)'. The source of their information is not stated, nor is it stated what clast size was analysed. Also they fail to mention whether their samples came from the First, Second or Third Cromer tills, or a combination of these (see Perrin *et al.* (1979) for definition of these lithological units). The latter omission is particularly significant as we have correlated the Second Cromer Till (Walcott Till Member) with the Lowestoft Formation (Moorlock *et al.*, 2000a; Lee *et al.*, 2004a).

Ehlers and Gibbard (1991). On page 18 of this paper the authors state 'The ice that deposited the North Sea Drift sediments characteristically contains a suite of igneous and metamorphic erratics of southern Norwegian origin. Some of these erratics, specifically rhomb porphyry and larvikite, can be traced to exposures in the Oslo area... These erratics are found at all exposures of the North Sea Drift Cromer Tills'. Ehlers and Gibbard also include a photograph of a rhomb porphyry (their figure 4), but the caption reads simply 'found at Cromer' without any indication as to whether the clast was found *in situ* or picked-up from the beach.

Hamblin (2000) and Moorlock et al. (2002). In his presidential address to the East Midlands Geological Society, Hamblin (2000) did indeed refer to the presence of rhomb porphyry clasts in the Happisburgh Till Member, and also to Scandinavian erratics in the 'Hanworth Till Member' (the Bacton Green Till Member of Lee *et al.*, 2004a) but he was, as others have done, simply reporting on the observations of others. Likewise, Moorlock *et al.* (2002) also mentioned the presence of rhomb porphyry in the 'Hanworth Till Member' following transmission of a television programme in which Dr Gibbard found an example of this rock type in the cliffs at West Runton.

A PLEA FOR INFORMATION ABOUT SCANDINAVIAN ERRATICS IN THE TILLS OF EAST ANGLIA

In 2001, Moorlock *et al.* (2001) attempted to introduce a debate and seek knowledge relating to the issue of Scandinavian erratics in Britain, and published a short letter in *Quaternary Newsletter* requesting anyone who had found *in situ* rhomb porphyry within the tills of north-east Norfolk to contact them. This request failed to elicit a single positive response, although we had emails from several researchers confirming an

absence of positive sightings.

None of the papers cited by Hoare & Connell (2005) conclusively records *in situ* clasts of undisputed Scandinavian origin within the earliest glacigenic deposits of northern East Anglia. In view of the ambiguities surrounding the geological archive, it was decided to develop our own data set, not only to provide a sound scientific basis for hypothesis testing, but also to enable the robust regional comparison and correlation of lithological and sedimentological data sets following standard geological practices (Bridgland, 1986; Gale & Hoare, 1991; Salvador, 1994; Jones *et al.*, 1999; Rawson *et al.*, 2002). It was for these reasons that we decided to rely on our own observations and analyses.

THE ANALYTICAL APPROACH USED BY THE BGS/ RHUL GROUP AND AN APPARENT FAILURE TO DISCOVER SCANDINAVIAN ERRATICS

Hoare & Connell (2005) make several valid points concerning the clast-poor nature of the 'North Sea Drift' group of tills, and the availability of clasts of sufficient size and number to enable the accurate identification of rare and significant erratic lithologies. However, the claims of Hoare & Connell that we overlooked these issues are false, as all were clearly recognised and understood by our research group during the planning stage of our work, and our research strategy was adapted accordingly to overcome them (Lee, 2003). As stated by Lee *et al.* (2002) and Lee (2003), quantitative counts were undertaken on till clast assemblages within the 4-8mm and 8-16mm gravel fractions, and within sands and gravels from the 8-16mm and 16-32mm clast fractions. However, all larger clasts that were collected as part of the sampling process were also examined, as well as a considerable emphasis placed upon collecting and identifying erratic cobbles and boulders from field exposures. A further crucial part of the research strategy was to use clast lithologies with heavy mineral and derived palynomorphs as part of a multi-proxy approach to sediment provenancing. It was concluded that this approach would reduce any potential and actual lithological sorting processes that may have operated within the glacial system and mean that the silt (palynomorph), sand (heavy mineral) and gravel-boulder size fractions could all be utilised to aid sediment provenancing (Lee, 2003). It was the application of this multi-proxy approach that led us to conclude, for example, that the Happisburgh and Corton Till members of the Happisburgh Formation were deposited by British rather than Scandinavian ice (Lee *et al.*, 2002, 2004a).

NEW FINDS OF SCANDINAVIAN ERRATICS IN THE GLACIOGENIC DEPOSITS OF EAST ANGLIA, AND THEIR SIGNIFICANCE

Since the paper by Lee *et al.* (2004a) was accepted for publication (12th July 2004) investigations by members of the research group have continued and have yielded two separate discoveries of Scandinavian erratics within the Happisburgh Formation. Firstly, a pebble of larvikite was found within the Happisburgh Till Member at Happisburgh (JR). Identification was confirmed by thin section analysis. Careful examination of the position of the clast, in the presence of other researchers, indicated that this could not be derived from the abundant blocks of larvikite that are used for sea defences along the north Norfolk coast. Secondly, a boulder of Drammensgranit was found, in the presence of a larger party, within the Corton Sand Member at Corton (JRL). A detailed account of this second discovery, its stratigraphic context, and the wider implications for the glacial history of the North Sea Basin have been submitted for publication elsewhere. Consequently, the discovery of a rhomb porphyry erratic within the Happisburgh Till Member by Hoare & Connell (2005) is in line with our own recent findings. Like Hoare & Connell, we do not believe that these discoveries negate our interpretation of a British-sourced Happisburgh Formation since the lithological constituents of these deposits are overwhelmingly British (Lee *et al.*, 2002). It is our belief that these relatively rare clasts are derived from Scandinavian sourced material already present in the North Sea basin.

OCCURRENCE AND SIGNIFICANCE OF SCANDINAVIAN ERRATICS WITHIN THE BRITON'S LANE SAND AND GRAVEL MEMBER (BLSG)

The history of research on the glacial deposits of northeast East Anglia, and the terminology of the deposits identified by this research are exceedingly complex. Lee (2003) and Lee *et al.* (2004a & b) provide a summary of the interpretation recommended at the present state of research. Essentially, there are three groups of sediment: the earlier shallow marine Wroxham Crag Formation and fluviatile Cromer Forest-bed Formation, the glacial, glaciofluvial and glaciolacustrine Happisburgh, Lowestoft and Sheringham Cliffs formations which were deposited by British ice, and the younger Briton's Lane Sand and Gravel (BLSG) which includes Scandinavian and British-sourced materials. The ice of the Last Glacial Maximum did not reach this area and there are no deposits of that age in this part of Norfolk. The Briton's Lane Sand and Gravel Member of the Briton's Lane Formation, which forms parts of the Cromer ridge contains a small but persistent presence of igneous and metamorphic erratics of Scandinavian origin. These include rhomb porphyry that has been recognised both as cobble-sized

erratics (Moorlock *et al.*, 2000b) and within the 8-16mm size fraction of quantitative stone counts from Weybourne (Pawley *et al.*, 2004) and Beeston Regis (Lee *et al.*, 2004). The latter occurrence is based upon the detailed provenancing and reclassification (JRL, SJP) of clasts that were originally classified as 'Igneous and Metamorphic' by Moorlock *et al.* (2000b). However, despite the presence of this Scandinavian material, the overwhelming source of the constituents of the deposit is from the British Isles (Lee *et al.*, 2004a).

At no point was the statement: "...provenance of the unit [described] as 'predominantly British with a minor Scandinavian component'..." included within Lee *et al.* (2004a) as cited by Hoare & Connell (2005, p. 9). Indeed, particular care was taken by Lee *et al.* (2004a) to simply describe the provenance of the clast assemblage and not to assign it to derivation from either the British or Scandinavian ice sheets. As suggested by Pawley *et al.* (2005), this reflects a new input of Scandinavian lithologies into northern East Anglia, however, it is unclear at present whether this represents a direct input from the Scandinavian Ice Sheet, or the recycling of Scandinavian materials from the North Sea Basin. Resolving this complex topic is one theme of the current research objectives of the BGS-RHUL group.

SUMMARY AND CONCLUSIONS

Historically, the reported occurrence of Scandinavian lithologies within the glacial deposits of northern Norfolk is long-standing, and has been accepted, since its inception, without rigorous scientific foundation. Careful examination of the literature reveals that the concept received widespread acceptance following stratigraphic studies in the nineteenth and early twentieth centuries by workers researching throughout eastern England. Essentially, these studies created a stratigraphic link between the 'North Sea Drift' (or Lower Glacial) of Norfolk with the 'Lower Glacial' of Yorkshire and County Durham (Buckland, 1823; Trimmer, 1858; Harmer, 1909), which are known to contain significant quantities of Scandinavian erratics (e.g. 'Basement Till' and 'Warren House Gill Till', Bowen, 1999). This misleading correlation has developed despite a vague and highly ambiguous literature base, that provides very little quantitative supporting data, and minimal site and stratigraphic context for reported finds in northern East Anglia (Moorlock *et al.*, 2001; Lee *et al.*, 2004a). It was on this basis that the BGS-RHUL research group undertook a systematic programme to investigate the lithology and provenance of glacial deposits in northern Norfolk.

The findings of this programme to date demonstrate that tills previously assigned to the 'North Sea Drift' are of British provenance and were deposited in association with

a British Ice Sheet flowing down the present east coast of England from central Scotland (Lee *et al*., 2002, 2004a). Extremely rare occurrences of Scandinavian erratics do occur within the oldest part of the glacial sequence as recent discoveries demonstrate. However, these are insignificant in terms of the provenance of the geological units (Hoare & Connell, 2005), and appear to represent the presence of Scandinavian ice within the North Sea basin on an earlier occasion. The apparent failure of the BGS-RHUL research group to discover and identify Scandinavian erratics within the deposits known as the 'North Sea Drift' is not due to poor scientific practice, as Hoare & Connell (2005) seem to imply, but due to their extreme rarity. This can be demonstrated by the fact that to date, only 2 confirmed and well documented *in situ* finds of Scandinavian erratics have been made within 36,000+ analysed clasts within pre-Briton's Lane Formation deposits. To these we must also add the finds of Hoare & Connell (2005). Scandinavian erratics are, however, relatively more common within the Briton's Lane Sand and Gravel Member of the Briton's Lane Formation. Members of the research group are currently attempting to establish whether this is a direct lithological input into northern East Anglia by a Scandinavian Ice Sheet, or whether, as seems to be the case with older glacial deposits, that Scandinavian erratics have been reworked by British ice from the area of the North Sea Basin.

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THE FIRST APPEARANCE OF SCANDINAVIAN INDICATORS IN EAST ANGLIA'S GLACIAL RECORD – REPLY

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INTRODUCTION

We are pleased that Lee *et al.* are now able to confirm that glacial erratics from Norwegian bedrock sources may be found in the Happisburgh Formation in East Anglia. Their discovery of a larvikite pebble in the Happisburgh Till (the oldest member of the formation) at Happisburgh and a Drammensgranit boulder in the Corton Sand at Corton may be added to the list of Scandinavian indicators that have been noted during the last century or so. These include our own record of a rhomb porphyry erratic in the Happisburgh Till at Happisburgh (Hoare & Connell, 2005).

We welcome this opportunity to expand upon points made in our first contribution to the debate (Hoare & Connell, 2005) and to respond to some of the issues raised here by Lee *et al.*

THE KERNEL OF AN IDEA

Our brief and necessarily highly selective literature review (Hoare & Connell, 2005, pp. 4-5) served to illustrate the birth and early development of the contention that particular erratics in the 'North Sea Drift', the earliest East Anglian glacial sediments, were derived from extra-British bedrock outcrops. Following an uncertain start (e.g. Buckland, 1823; Lyell, 1840; Trimmer, 1847; 1851; 1858), the stratigraphic distribution of these indicator erratics and a sound knowledge of their ultimate provenance were established. We believe that this early published material may be exploited by modern workers.

THE CONTINUED VALUE OF EARLY PUBLISHED ACCOUNTS

Pioneering geologists engaged in East Anglian Quaternary research undeniably failed to unravel the full complexity of the glacial succession. However, a significant number of

them referred to the erratic content of particular beds and did not invariably base their work on miscorrelations of the 'North Sea Drift' with **younger**, Scandinavian indicator-bearing deposits in County Durham, Yorkshire and Lincolnshire (*contra* Lee *et al.*, pp. 44-45, 50-51). In his record of the oldest glacial sediments, Buckland (1823) described a tough bluish clay 'in the localities here enumerated' (these included 'the shores of Norfolk, Suffolk, and Essex') through which are dispersed irregularly large blocks and pebbles of many varieties of primitive and transition rocks which can only be accounted for by supposing them to have been drifted from Norway (Buckland, 1823, pp. 192, 193, 198-199; see also Lyell, 1840, p. 376). It is Buckland's observations on the petrography of the deposits rather than his mistaken belief in their diluvial origin (see, for example, Buckland, 1823, p. 193) that are of significance in this context. Trimmer provided descriptions of *The Lower Drift — Till or Boulder Clay*, the lowest member of the northern drift, exposed in cliffs near Happisburgh (Trimmer, 1847, pp. 461-462) and at Gorleston-on-Sea (Trimmer, 1858, pp. 171-172). The erratic content is said to include 'foreign detritus' consisting of rock types which occur no nearer than Scotland or Scandinavia (Trimmer, 1847, p. 461; 1851, p. 21; 1858, p. 171).

Sherborne (1887) collected a rhomb porphyry clast from an exposure of 'Cromer Boulder-Drift' near <u>East</u> Runton (*contra* Lee *et al.*, p. 45), where the cliff sediments are composed almost exclusively of the Sheringham Cliffs Formation (Lee *et al.*, 2004a, fig. 4). Harmer (1928, p. 100) described in some detail the location and stratigraphic horizon at which a rhomb porphyry cobble (Fig. 1) was found in the 'North Sea Drift' ('Norwich Brickearth') in a brickyard at Hellesdon, Norwich (TG 220116) in August 1903, a discovery first publicised in 1904 (Harmer, 1904, p. 309; 1928, pp. 91, 100; Kendall, 1904, p. 236). (Kendall mistakenly reported that the indicator came from 'chalky boulder clay', an error reproduced by Phemister (1926, p. 448)). The specimen was donated to the Norwich Castle Museum (Harmer, 1928, p. 91).

Boswell (1914; 1916) and Solomon (1932) described the Quaternary stratigraphy of parts of East Anglia but, as Lee *et al.* (p. 46) point out, they failed to offer new information on the type, locality or stratigraphic position of Scandinavian erratics.

RIGOUR IN THE IDENTIFICATION OF INDICATORS

Whilst we are agreed that great care was taken by early key workers to ensure the correct identification of Scandinavian erratics recorded in East Anglia, Lee *et al.*'s (p. 45) emphasis on the '... series of East Coast erratics ...' collected by Stather and Sheppard and examined by Professor W.C. Brøgger in Christiania [Oslo] (Kendall, 1899, p. 553)

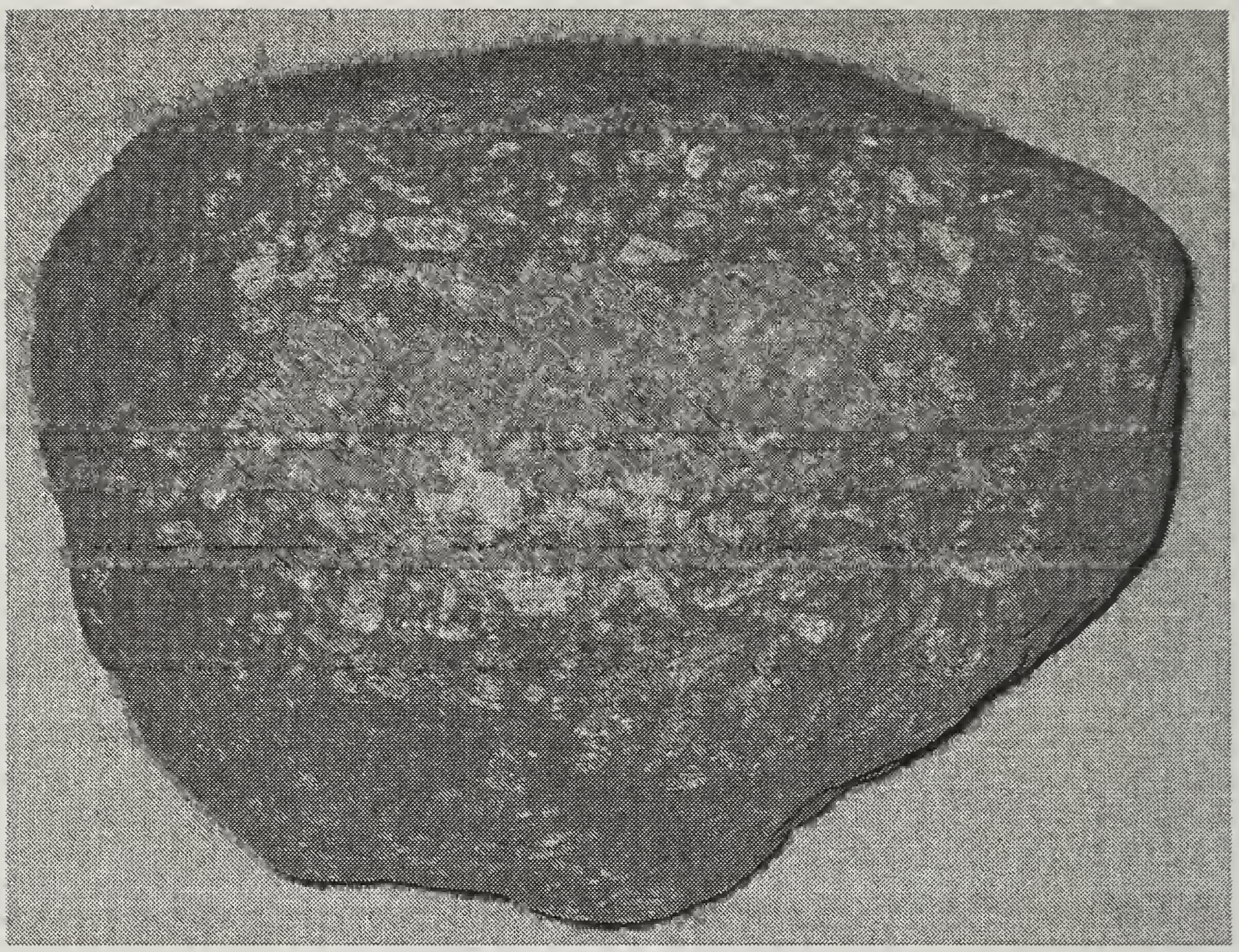

Fig. 1. Rhomb porphyry cobble from the 'North Sea Drift' ('Norwich Brickearth'), Cunnell's brickyard, Hellesdon, Norwich (TG 220116), August 1903 (Norwich Castle Museum Accession Number NWHCM : 2005.438).

merely clouds the issue. Stather and Sheppard usually conducted their fieldwork in Yorkshire and Lincolnshire, but we cannot assume that these counties were the only source of the material studied by Brøgger. However, we do know that they routinely gathered erratics from fields, bays and beaches as well as from outcrops (Kendall, 1899, pp. 554-555). The work of P.F. Kendall, the long-serving Secretary of the Committee for Erratic Blocks of the British Isles, is of greater significance in this context. He spent a month in 1897 collecting samples from bedrock outcrops between Christiania and Christiansand. He returned with a large quantity of material illustrating important petrological types for comparison with the erratics of the east coast of England. Approximately 300 specimens were distributed amongst English workers in glacial geology; other sets of erratics were to be lodged in public museums (Kendall, 1899, p. 553). Thus Kendall was able to confirm the identity of the Hellesdon rhomb porphyry (see above) (Harmer, 1904, p. 309).

THE VALUE OF ARCHIVED SPECIMENS

So long as it is possible to verify the stratigraphic details of Scandinavian indicator finds and to confirm their identity, early discoveries may be of considerable importance. The Norwich Castle Museum's erratic collection is currently housed in temporary accommodation at the Norfolk Rural Life Museum at Gressenhall. It includes Harmer's rhomb porphyry erratic from the 'North Sea Drift' at Hellesdon (Fig. 1), a well-rounded clast measuring ~180 x 145 x 90 mm in which numerous rhombic phenocrysts show flow alignment.

The identity of Sherborne's (1887) rhomb porphyry clast from 'Cromer Boulder-Drift' near East Runton is beyond question. The fragment of the specimen that the discoverer sent to the Natural History Museum (Accession Number BM 67432) measures 54 x 47 x 30 mm. It is regrettable that the stratigraphic position of one of the first examples of this rock type to be recorded as an erratic in East Anglia cannot be established with absolute confidence.

A considerable number of Scandinavian indicators from East Anglian sites held by museums and in private hands is currently being investigated by the authors.

THE RECENT QUEST FOR SCANDINAVIAN INDICATORS IN EAST ANGLIA

The Happisburgh Till Member

The presence of Scandinavian indicators in the lowest members of the Happisburgh Formation cannot be doubted. Their infrequent occurrence is of far less relevance than their reliable identification. The intention of our first paper was to demonstrate that whilst they may not always be easily found in the Happisburgh Till, published evidence and surviving specimens held by institutions and individuals are available. However, we also believe that rhomb porphyry, larvikite and other indicators are not especially scarce in the cliff faces of eastern Norfolk, as demonstrated by a further recent discovery of a rhomb porphyry clast in the Happisburgh Till at Happisburgh (Norwich Castle Museum Accession Number NWHCM : 2005.437) (work in progress by Hoare, Larkin and Connell) and by Lee *et al.*'s (p. 49) finds.

'The Hanworth Till Member'

Lee *et al.* (p. 47) imply that Moorlock *et al.*'s (2002) belief in the existence of rhomb porphyry clasts in the Hanworth Till Member (the Bacton Green Till Member of Lee *et al.*, 2004a, table 11) was based on Dr P.L. Gibbard's televised discovery of such an erratic at West Runton. On the contrary, Moorlock *et al.* (2002) made no reference to this event. Furthermore, Moorlock *et al.* (2000a, p. 54; 2000b, p. 117) acknowledged Phil Gibbard's word that '... large clasts of rhomb porphyry ... are present in the Third Cromer Till ... at West Runton'.

The Briton's Lane Sand and Gravel Member

Lee *et al.* (2004a, table 8) recorded Scandinavian igneous, metamorphic and sedimentary clasts in two samples of the 8-16 mm fraction of the Briton's Lane Sand and Gravel Member: they make up 0.1% of the material in samples BL2 (Briton's Lane, Beeston Regis) and WC3 (Weybourne Cliffs). This exotic fraction includes a single rhomb porphyry clast at Weybourne (Pawley *et al.*, 2004, pp. 31, 36). Whilst the proportions are 'small' (Lee *et al.*, p. 49), they do not appear to be 'persistent' (*contra* Lee *et al.*, p. 49) as none was found in samples BL1, HA1 (Hanworth) and WR1 (West Runton) (Lee *et al.*, 2004a, table 8) (but see below).

In expressing the relative frequency of Scandinavian erratics as percentages to one decimal place, Lee *et al.* (2004a, table 8) imply an (apparent) accuracy of one part in a thousand in counts of 1863 (BL2) and 668 (WC3) clasts. However, the percentage error associated with estimating the true (real) frequency of rare («1%) indicators in a sediment, even in counts of 2141 clasts (BL1), is very large indeed (Dryden, 1931; Bridgland, 1986, fig. 1). The (apparent) great accuracy expressed by Lee *et al.* (2004a, table 8) is therefore unjustified. Determining frequencies in any one sample to much less than 5% error would be, in Dryden's (1931, p. 237) words '... a simple waste of time'. Although Scandinavian 'indicators' (often merely high-grade metamorphic lithologies of non-Scottish origin) do not appear to be present at all four Briton's Lane Sand and Gravel Member sites, examination of samples of adequate size may reveal a common presence: the problem is one of sampling error, of ensuring that an average (representative) sample has been secured.

In a '...collection of 250 large pebble- to cobble-sized ...' exotic clasts from Briton's Lane, ~70% were composed of igneous lithologies including an unspecified number of 'rhomb porphyry' clasts (Moorlock *et al.*, 2000b, p. 115): 'about three' rhomb porphyries and four 'Scandinavian gneisses' out of >250 (*sic*) cobble to boulder size erratics were identified (S.M. Pawley, personal communication, February 2005).

Moorlock *et al.* (2000b, table 13) noted a significant difference in the igneous and metamorphic component of the 8-16 mm (3.8%) and 16-32 mm fraction (0.0%) of the Briton's Lane Sand and Gravel. It is conceivable, therefore, that the large pebble to cobble fraction contains a different proportion again. Hoare & Connell (2005, p. 8) discuss the relationship of gravel composition with clast-size examined.

DISCUSSION AND CONCLUSIONS

Whilst Scandinavian crystalline (rhomb porphyry, larvikite, high-grade metamorphic) lithologies were not found in the 4-8 and 8-16 mm fractions of the Happisburgh Till at Happisburgh and Trimingham (Lee *et al.*, 2002, table 2), it has yet to be demonstrated by statistical means that Scandinavian erratics are relatively more common within the Briton's Lane Sand and Gravel than in the Happisburgh Till (*contra* Lee *et al.*, p. 51). Lee *et al.*'s sample sizes are adequate to determine the broad distribution of lithologies. The probable error associated with the abundant erratic species will be much lower than that of the scarce ones; the discovery of Scandinavian material will have been a matter of chance. In the case of the less common lithologies such as Norwegian indicators, and particularly when their presence or absence is the main criterion, a search of exposures is the more rewarding strategy; all recent finds of Norwegian clasts in members of the Happisburgh Formation by the present authors and by the BGS-RHUL team have resulted from outcrop searches.

It has been established beyond reasonable doubt that the tills of the Happisburgh Formation were deposited by a British ice sheet (Lee *et al.*, 2002). The extra-British material which reached the east coast of England and was transported into the very heart of East Anglia is likely to have had a broken journey (Boswell, 1916, p. 80). The nature and timing of the event(s) that led to the transport of Norwegian erratics to English and Scottish shores have still to be identified. The overwhelming source of the constituents of the Briton's Lane Sand and Gravel Member is also from the British Isles (Lee *et al.*, 2004a, table 13). In this regard, the Happisburgh Formation is no different from the Briton's Lane Sand and Gravel. We were surprised, therefore, that Lee *et al.* (p. 50) should complain that we assert (Hoare & Connell, 2005, p. 9) that they refer to the provenance of the Briton's Lane material as 'predominantly British with a minor Scandinavian component'. We simply ask them to read their summary of this unit (Lee *et al.*, 2004a, table 13), and we deny any misinterpretation of their account. The Scandinavian indicators in the lowest members of the Happisburgh Formation were susceptible to reworking into younger units. We await with interest to discover if the

Norwegian erratics in the Briton's Lane Sand and Gravel are considered to be the result of such recycling or of a fresh glacial introduction (Lee *et al.*, p. 50).

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Copies of the Bulletin (including older back copies) can be obtained from the editor at the address on p.1; it is issued free to members.

The photograph on the front cover is a tooth from the Lower Cretaceous shark *Notorynchus aptiensis* discovered in the Red Chalk at Hunstanton by Thomas Knight. This rare find is discussed in the article by Smart in this issue of the Bulletin. The photograph was taken by Dr Kevin Knight.

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